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TO: Examiner Prasad	*FAX NUMBER:* 571 273-2099
DATE: June 14, 2004	*PHONE NUMBER:* 571 272-2099
FROM: Monica Grewal	*TOTAL NO. OF PAGES INCLUDING COVER:* 67
RE: Application # 10/035,031	*CLIENT/MATTER NUMBER:* 061408.2004-102

☐ URGENT ☒ FOR REVIEW ☐ PLEASE COMMENT ☐ PLEASE REPLY ☐ PLEASE RECYCLE

In re: Application #10/035,031
Docket # 061408.2004-102
Inventor: Steven John Schray
Title: Module and Housing for DWDM Equipment

Dear Examiner Prasad:

Per our conversation, attached to this fax, please find reference AN (WO 01/14921 A1) as listed on our IDS dated May 25, 2004. Please feel free to call Attorney Grewal if you have any additional questions regarding this IDS.

Thank you.

Sharon Lloyd
Assistant to Monica Grewal

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PAGE 1/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 March 2001 (01.03.2001)

PCT

(10) International Publication Number
WO 01/14921 A1

(51) International Patent Classification[7]: G02B 6/34

(21) International Application Number: PCT/US00/14815

(22) International Filing Date: 31 May 2000 (31.05.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/382,624 25 August 1999 (25.08.1999) US

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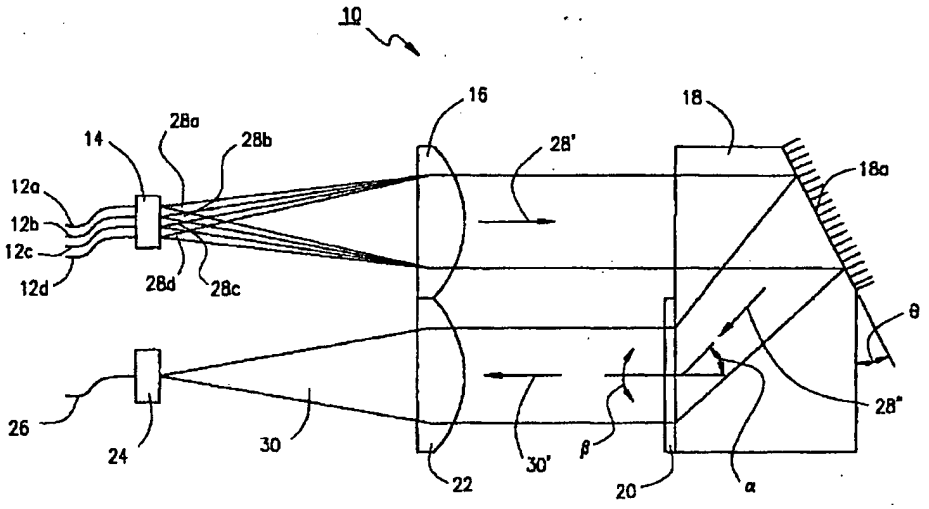
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*
— *Before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: WAVELENGTH DIVISION MULTIPLEXER/DEMULTIPLEXER USING HOMOGENEOUS REFRACTIVE INDEX LENSES AND TRANSMISSION GRATING



(57) Abstract: A wavelength division multiplexing device (10) comprises a homogeneous refractive index collimating lens (16) for collimating a plurality of monochromatic optical beams (28), a mirror (18a), a diffraction grating (20), for combining the plurality of collimated, monochromatic optical beams into a multiplexed, polychromatic optical beam (30), and a homogeneous refractive index lens L (22) for focusing the multiplexed, output beam. The WDM is connected via coupling devices (14, 24) to optical fiber (12, 16) or active devices like photodiodes or lasers. In a preferred embodiment, the lenses are made of a material having a high refractive index to keep spherical aberrations low. The WDM may also contain additional boot lenses made of lower refractive index material.

WO 01/14921 A1

WAVELENGTH DIVISION MULTIPLEXER/DEMULTIPLEXER USING HOMOGENEOUS REFRACTIVE INDEX LENSES AND TRANSMISSION GRATING

FIELD OF THE INVENTION

The present invention relates generally to wavelength division multiplexing/demultiplexing and, more particularly, to wavelength division multiplexing/demultiplexing devices using dual homogeneous refractive index lenses.

BACKGROUND OF THE INVENTION

Wavelength division multiplexing (WDM) is a rapidly emerging technology that enables a very significant increase in the aggregate volume of data that can be transmitted over optical fibers. Prior to the use of WDM, most optical fibers were used to unidirectionally carry only a single data channel at one wavelength. The basic concept of WDM is to launch and retrieve multiple data channels in and out, respectively, of an optical fiber. Each data channel is transmitted at a unique wavelength, and the wavelengths are appropriately selected such that the channels do not interfere with each other, and the optical transmission losses of the fiber are low. Today, commercial WDM systems exist that allow for the transmission of 2 to 100 simultaneous data channels.

WDM is a cost-effective method of increasing the volume of data (commonly termed bandwidth) transferred over optical fibers. Alternate competing technologies for increasing bandwidth include the burying of additional fiber optic cable or increasing the optical transmission rate over optical fiber. The burying of additional fiber optic cable is quite costly as it is presently on the order of $15,000 to $40,000 per kilometer. Increasing the optical transmission rate is limited by the speed and economy of the electronics surrounding the fiber optic

PAGE 3/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

system. One of the primary strategies for electronically increasing bandwidth has been to use time division multiplexing (TDM), which groups or multiplexes multiple lower rate electronic data channels together into a single very high rate channel. This technology has for the past 20 years been very effective for increasing bandwidth. However, it is now increasingly difficult to improve transmission speeds, both from a technological and an economical standpoint. WDM offers the potential of both an economical and technological solution to increasing bandwidth by using many parallel channels. Further, WDM is complimentary to TDM. That is, WDM can allow many simultaneous high transmission rate TDM channels to be passed over a single optical fiber.

The use of WDM to increase bandwidth requires two basic devices that are conceptually symmetrical. The first device is a wavelength division multiplexer. This device takes multiple beams, each with discrete wavelengths that are initially spatially separated in space, and provides a means for spatially combining all of the different wavelength beams into a single polychromatic beam suitable for launching into an optical fiber. The multiplexer may be a completely passive optical device or may include electronics that control or monitor the performance of the multiplexer. The input to the multiplexer is typically accomplished with optical fibers, although laser diodes or other optical sources may also be employed. As mentioned above, the output from the multiplexer is a single polychromatic beam which is typically directed into an optical fiber.

The second device for WDM is a wavelength division demultiplexer. This device is functionally the opposite of the wavelength division multiplexer. That is, the wavelength division demultiplexer receives a polychromatic beam from an optical fiber and provides a means of

PAGE 4/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

spatially separating the different wavelengths of the polychromatic beam. The output from the demultiplexer is a plurality of monochromatic beams which are typically directed into a corresponding plurality of optical fibers or photodetectors.

During the past 20 years, various types of WDMs have been proposed and demonstrated. For example, (1) W.J. Tomlinson, *Applied Optics*, Vol. 16, No. 8, pp. 2180-2194 (Aug. 1977); (2) A.C. Livanos et al., *Applied Physics Letters*, Vol. 30, No. 10, pp. 519-521 (15 May 1977); (3) H. Ishio et al., *Journal of Lightwave Technology*, Vol 2, No. 4, pp. 448-463 (Aug. 1984); (4) H. Obara et al., *Electronics Letters*, Vol. 28, No. 13, pp. 1268-1270 (18 June 1992); (5) A.E. Willner et al., *IEEE Photonics Technology Letters*, Vol. 5, No. 7, pp. 838-841 (July 1993); and (6) Y.T. Huang et al., *Optical Letters*, Vol. 17, No. 22, pp. 1629-1631 (15 Nov. 1992), all disclose some form of WDM device and/or method. However, most of the WDM devices and/or methods disclosed in the above-listed publications are classical optics-based WDM approaches which employ very basic lenses that are adequate only for use with multimode optical fibers and are inadequate for use with single mode optical fibers because the core diameter of a single mode optical fiber (i.e., typically 8 μm) is much smaller than the core diameter of a multimode optical fiber (i.e., typically 62.5 μm). That is, due to the very basic lenses employed therein, WDM devices incorporating the principles set forth in the classical optics-based WDM approaches disclosed in the above-listed publications are unable to receive and transmit optical beams from and to single mode optical fibers, respectively, without incurring unacceptable amounts of insertion loss and channel crosstalk. These unacceptable levels of insertion loss and channel crosstalk are largely due to the inadequate imaging

PAGE 5/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

capabilities of these very basic lenses, which are typically formed of standard optical glass materials.

One proposed solution to the above-described optical imaging problem has been to add additional lenses formed of standard optical glass materials to WDM devices, thereby resulting in WDM devices having doublet, triplet, and even higher number lens configurations. By adding these additional lenses to WDM devices, wherein the added lenses typically have alternating high and low refraction indexes, aberrations caused mainly by the spherical nature of the lenses are effectively canceled out. However, an increased cost is associated with adding these additional lenses due to the direct cost of the additional lenses, as well as the indirect costs associated with the increased complexity and resulting decreased manufacturability of WDM devices having multiple lenses.

Another proposed solution to the above-described optical imaging problem has been to use gradient refractive index lenses (e.g., Gradium lenses) in WDM devices. The use of these gradient refractive index lenses results in a significant improvement in the quality of the imaging system within WDM devices. However, costs associated with manufacturing these gradient refractive index lenses is significantly greater than the costs associated with manufacturing standard homogeneous refractive index lenses, despite the fact that both are typically formed of standard optical glass materials.

In view of the foregoing, there remains a real need for a WDM device which possesses or allows for all the characteristics of: low cost, component integration, environmental and thermal stability, low channel crosstalk, low channel signal loss, ease of interfacing, large number of channels, and narrow channel spacing. Accordingly, it would be desirable to provide a WDM device which overcomes the above-described inadequacies and shortcomings, while

PAGE 6/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

possessing or allowing for all of the above-stated characteristics.

OBJECTS OF THE INVENTION

The primary object of the present invention is to provide wavelength division multiplexing/demultiplexing devices which use dual homogeneous refractive index lenses to achieve increased device performance, as well as reduced device cost, complexity, and manufacturing risk.

The above-stated primary object, as well as other objects, features, and advantages, of the present invention will become readily apparent from the following detailed description which is to be read in conjunction with the appended drawings.

SUMMARY OF THE INVENTION

According to the present invention, a wavelength division multiplexing device is provided. In a preferred embodiment, the wavelength division multiplexing device comprises a homogeneous refractive index collimating lens for collimating a plurality of monochromatic optical beams, a diffraction grating for combining the plurality of collimated, monochromatic optical beams into a multiplexed, polychromatic optical beam, and a homogeneous refractive index focusing lens for focusing the multiplexed, polychromatic optical beam.

The homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens are preferably plano-convex lenses, convex-plano lenses, or bi-convex lenses, although other lens configurations are possible. For example, the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens can be spherical or aspherical. Also, the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens have high

PAGE 7/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

indexes of refraction and preferably operate in the infrared (IR) region of the electromagnetic spectrum since this is the region where the power loss (attenuation) and dispersion of silica-based optical fibers is very low. Accordingly, the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens are typically formed of a high index of refraction glass material selected from the group consisting of SF59, PBH71, LAH78, and other high index of refraction glass materials that efficiently transmit optical beams in the infrared (IR) region of the electromagnetic spectrum. The diffraction grating is preferably a transmissive diffraction grating.

In accordance with other aspects of the present invention, the wavelength division multiplexing device can be provided in integrated form. That is, an integrated wavelength division multiplexing device can be provided comprising a homogeneous refractive index collimating lens for collimating a plurality of monochromatic optical beams, a first homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the plurality of collimated, monochromatic optical beams from the homogeneous refractive index collimating lens, wherein the first homogeneous refractive index boot lens has a planar exit surface, and a diffraction grating formed at the planar exit surface of the first homogeneous refractive index boot lens for combining the plurality of collimated, monochromatic optical beams into a multiplexed, polychromatic optical beam.

In accordance with further aspects of the present invention, the first homogeneous refractive index boot lens can be incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index

PAGE 8/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

collimating lens has the planar exit surface at which the diffraction grating is formed.

In accordance with still further aspects of the present invention, the integrated wavelength division multiplexing device can include a second homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the plurality of monochromatic optical beams to the homogeneous refractive index collimating lens. The second homogeneous refractive index boot lens preferably has a planar entry surface for accepting the plurality of monochromatic optical beams from at least one optical source (e.g., optical fibers, laser diodes). Alternatively, the integrated wavelength division multiplexing device may do without the second homogeneous refractive index boot lens, and the homogeneous refractive index collimating lens can have a planar entry surface for accepting the plurality of monochromatic optical beams from at least one optical source.

In accordance with still further aspects of the present invention, the diffraction grating is preferably a transmissive diffraction grating, and the integrated wavelength division multiplexing device can include a transmissive element associated with the transmissive diffraction grating, wherein the transmissive element preferably has at least one reflective surface for reflecting the multiplexed, polychromatic optical beam. The integrated wavelength division multiplexing device can then also include a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the multiplexed, polychromatic optical beam from the transmissive element, and a homogeneous refractive index focusing lens affixed to the second homogeneous refractive index boot lens for focusing the multiplexed, polychromatic optical beam. The second homogeneous

PAGE 9/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

refractive index boot lens can be incorporated into the homogeneous refractive index focusing lens such that the homogeneous refractive index focusing lens is affixed to the transmissive element. The integrated wavelength division multiplexing device can then further include a third homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the focused, multiplexed, polychromatic optical beam from the homogeneous refractive index focusing lens. The third homogeneous refractive index boot lens preferably has a planar exit surface for outputting the focused, multiplexed, polychromatic optical beam to at least one optical receiver (e.g., optical fibers, photodetectors). Alternatively, the integrated wavelength division multiplexing device may do without the third homogeneous refractive index boot lens, and the homogeneous refractive index focusing lens can have a planar exit surface for outputting the focused, multiplexed, polychromatic optical beam to at least one optical receiver.

In accordance with other aspects of the present invention, the wavelength division multiplexing device can be provided in an alternative integrated form. That is, an alternative integrated wavelength division multiplexing device can be provided comprising a homogeneous refractive index focusing lens for focusing a multiplexed, polychromatic optical beam, a first homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the multiplexed, polychromatic optical beam to the homogeneous refractive index focusing lens, wherein the first homogeneous refractive index boot lens has a planar entry surface, and a diffraction grating formed at the planar entry surface of the first homogeneous refractive index boot lens for combining a plurality of monochromatic optical beams into the multiplexed, polychromatic optical beam.

PAGE 10/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

In accordance with further aspects of the present invention, the first homogeneous refractive index boot lens can be incorporated into the homogeneous refractive index focusing lens such that the homogeneous refractive index focusing lens has the planar entry surface at which the diffraction grating is formed.

In accordance with still further aspects of the present invention, the diffraction grating is preferably a transmissive diffraction grating, and the alternative integrated wavelength division multiplexing device can include a transmissive element associated with the transmissive diffraction grating, wherein the transmissive element preferably has at least one reflective surface for reflecting the plurality of monochromatic optical beams toward the transmissive diffraction grating. The alternative integrated wavelength division multiplexing device can then also include a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the plurality of monochromatic optical beams to the transmissive element, and a homogeneous refractive index collimating lens affixed to the second homogeneous refractive index boot lens for collimating the plurality of monochromatic optical beams prior to transmission by the second homogeneous refractive index boot lens. The second homogeneous refractive index boot lens can be incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index collimating lens is affixed to the transmissive element.

At this point it should be noted that the above-described wavelength division multiplexing device, integrated wavelength division multiplexing device, and alternative integrated wavelength division multiplexing device are all bidirectional devices. Thus, the wavelength division multiplexing device can also be a wavelength

PAGE 11/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

division demultiplexing device, the integrated wavelength division multiplexing device can also be an integrated wavelength division demultiplexing device, and the alternative integrated wavelength division multiplexing device can also be an alternative integrated wavelength division demultiplexing device. Further, all of the above-described devices can be used simultaneously as both a multiplexer and a demultiplexer.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to facilitate a fuller understanding of the present invention, reference is now made to the appended drawings. These drawings should not be construed as limiting the present invention, but are intended to be exemplary only.

Figure 1a is a side view of a wavelength division multiplexing device having dual plano-convex homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 1b is a perspective end view of a portion of the wavelength division multiplexing device shown in Figure 1a.

Figure 2a is a perspective view of a coupling device containing a plurality of laser diodes for replacing the plurality of optical input fibers in the multiplexing device shown in Figure 1a.

Figure 2b is a perspective view of a coupling device containing a plurality of photodetectors for replacing the plurality of optical input fibers in the demultiplexing device shown in Figure 3.

Figure 3 is a side view of a wavelength division demultiplexing device having dual plano-convex homogeneous refractive index collimating/focusing lenses and a

PAGE 12/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

transmissive diffraction grating in accordance with the present invention.

Figure 4 is a side view of an integrated wavelength division multiplexing device having dual plano-convex homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 5 is a side view of an integrated wavelength division multiplexing device having dual extended plano-convex homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 6 is a side view of a wavelength division multiplexing device having dual convex-planc homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 7 is a side view of an integrated wavelength division multiplexing device having dual convex-plano homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 8 is a side view of an integrated wavelength division multiplexing device having dual extended convex-plano homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 9 is a side view of a wavelength division multiplexing device having dual bi-convex homogeneous refractive index collimating/focusing lenses and a transmissive diffraction grating in accordance with the present invention.

Figure 10 is a side view of an integrated wavelength division multiplexing device having dual bi-convex homogeneous refractive index collimating/focusing lenses

PAGE 13/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

and a transmissive diffraction grating in accordance with the present invention.

Figure 11 is a side view of an integrated in-line wavelength division multiplexing device having dual bi-convex homogeneous refractive index lenses, a transmissive diffraction grating, and a reflecting element in accordance with the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to Figure 1a, there is shown a side view of a preferred embodiment of a wavelength division multiplexing device 10 in accordance with the present invention. The multiplexing device 10 comprises a plurality of optical input fibers 12, an input fiber coupling device 14, a plano-convex homogeneous refractive index collimating lens 16, a reflecting element 18 having a reflecting surface 18a, a transmissive diffraction grating 20, a plano-convex homogeneous refractive index focusing lens 22, an output fiber coupling device 24, and a single optical output fiber 26.

At this point it should be noted that the optical input fibers 12 and the optical output fiber 26, as well as any other optical fibers described herein as being used in conjunction with WDM devices in accordance with the present invention, are single mode optical fibers. Of course, however, this does not limit the present invention WDM devices to use with only single mode optical fibers. For example, the present invention WDM devices can also be used with multimode optical fibers.

It should also be noted that the multiplexing device 10, as well as any other WDM devices described herein as being WDM devices in accordance with the present invention, is operating in the infrared (IR) region of the electromagnetic spectrum as a dense wavelength division multiplexing (DWDM) device (i.e., operating with data

PAGE 14/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

channels having channel spacings of 1 nm or less). Of course, however, this does not limit the present invention WDM devices to being only DWDM devices. For example, the present invention WDM devices can also be standard WDM devices (i.e., operating with data channels having channel spacings greater than 1 nm).

Returning to Figure 1a, the plurality of optical input fibers 12 are grouped into a one-dimensional input fiber array (i.e., a 1 x 4 array) by the input fiber coupling device 14, while the single optical output fiber 26 is secured to the output fiber coupling device 24. Both the input fiber coupling device 14 and the output fiber coupling device 24 are used for purposes of ease of optical fiber handling and precision placement, and can be formed of, for example, a silicon V-groove assembly. Referring to Figure 1b, there is shown a perspective end view of a portion of the multiplexing device 10 revealing how the plurality of optical input fibers 12 are grouped into the one-dimensional input fiber array by the input fiber coupling device 14, and how the single optical output fiber 26 is secured to the output fiber coupling device 24. Figure 1b also shows a monochromatic optical input beam 28 being transmitted from each of the plurality of optical input fibers 12, and a single multiplexed, polychromatic optical output beam 30 being transmitted to the single optical output fiber 26.

Each of the monochromatic optical input beams 28 being transmitted from the plurality of optical input fibers 12 is carrying a single channel of data at a unique wavelength, which is preferably, but not required to be, within the infrared (IR) region of the electromagnetic spectrum. The single channel of data that is being carried by each monochromatic optical input beam 28 is superimposed on each corresponding unique wavelength by means (e.g., laser diodes connected to the plurality of optical input

PAGE 15/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

fibers 12), which are not shown here and which do not form a part of this invention, but are well known in the art. The unique wavelengths of the monochromatic optical input beams 28 are appropriately preselected such that the data channels do not interfere with each other (i.e., there is sufficient channel spacing), and the optical transmission losses through both the optical input fibers 12 and the optical output fiber 26 are low, as is also well known in the art.

The single multiplexed, polychromatic optical output beam 30 being transmitted to the single optical output fiber 26 is carrying a plurality of channels of data at the unique wavelengths of each of the plurality of monochromatic optical input beams 28. The plurality of monochromatic optical input beams 28 are combined into the single multiplexed, polychromatic optical output beam 30 through the combined operation of the plano-convex homogeneous refractive index collimating lens 16, the transmissive diffraction grating 20, and the plano-convex homogeneous refractive index focusing lens 22, as will be described in more detail below.

Referring again to Figure 1a, each of the plurality of monochromatic optical input beams 28 are transmitted from their corresponding optical input fiber 12 into the air space between the input fiber coupling device 14 and the plano-convex homogeneous refractive index collimating lens 16. Within this air space, the plurality of monochromatic optical input beams 28 are expanded in diameter until they become incident upon the plano-convex homogeneous refractive index collimating lens 16. The plano-convex homogeneous refractive index collimating lens 16 collimates each of the plurality of monochromatic optical input beams 28, and then transmits each of a plurality of collimated, monochromatic optical input beams 28' to the reflecting element 18.

PAGE 16/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

The reflecting element 18 is fabricated of a transmissive material such as, for example, a standard optical glass material like BK7 (manufactured by Schott Glass Technologies, Inc. with n = 1.501 @ 1550 nm). Thus, each of the plurality of collimated, monochromatic optical input beams 28' is transmitted through the reflecting element 18 toward the reflecting surface 18a, which is formed at a reflecting angle, θ, on a beveled edge of the reflecting element 18. The reflecting surface 18a reflects each of the plurality of collimated, monochromatic optical input beams 28' such that a plurality of reflected, collimated, monochromatic optical input beams 28'' are transmitted through the reflecting element 18 toward the transmissive diffraction grating 20. The reflecting angle, θ, is chosen based upon the desired center wavelength diffraction angle of the transmissive diffraction grating 20, as will be described in more detail below.

The transmissive diffraction grating 20 operates to angularly disperse the plurality of reflected, collimated, monochromatic optical input beams 28'' by an amount that is dependent upon the wavelength of each of the plurality of reflected, collimated, monochromatic optical input beams 28''. That is, the transmissive diffraction grating 20 operates according to the well known diffraction grating equation,

$$m\lambda = d(\sin \alpha + \sin \beta)$$

wherein m is the diffraction order, λ is the wavelength, d is the diffraction grating groove spacing, α is the incident angle with respect to the diffraction grating normal, and β is the diffraction angle with respect to the diffraction grating normal. For the multiplexing device 10 shown in Figure 1a, the diffraction angle, β, is desired to be 0°, so the incident angle, α, is equal to 45° for a

PAGE 17/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

center wavelength of 1550 nm and a diffraction grating having an order of 1 and a groove spacing of 0.65 μm. The reflecting angle, θ, is equal to one-half of the incident angle, α, for the multiplexing device 10 shown in Figure 1a. So the reflecting angle, θ, is equal to 22.5° for the multiplexing device 10 shown in Figure 1a. Of course, the present invention is not limited to the values just described as they are provided for purposes of illustration only.

At this point it should be noted that the transmissive diffraction grating 20 can be formed from a variety of materials and by a variety of techniques. For example, the transmissive diffraction grating 20 can be formed by a three-dimensional hologram in a polymer medium, or by replicating a mechanically ruled master with a polymer material. The transmissive diffraction grating 20 could then be joined or affixed to the surface of the reflecting element 18 using optical cement or some other optically transparent bonding technique. Alternatively, the transmissive diffraction grating 20 can be formed directly on the surface of the reflecting element 18, thereby avoiding the joining or affixing of the transmissive diffraction grating 20 to the surface of the reflecting element 18.

As previously mentioned, the transmissive diffraction grating 20 operates to angularly disperse the plurality of reflected, collimated, monochromatic optical input beams 28''. Thus, the transmissive diffraction grating 20 removes the angular separation of the plurality of reflected, collimated, monochromatic optical input beams 28'', and transmits a single collimated, polychromatic optical output beam 30' towards the plano-convex homogeneous refractive index focusing lens 22. The single collimated, polychromatic optical output beam 30' contains each of the unique wavelengths of the plurality of

PAGE 18/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

reflected, collimated, monochromatic optical input beams 28''. Thus, the single collimated, polychromatic optical output beam 30' is a single collimated, multiplexed, polychromatic optical output beam 30'. The plano-convex homogeneous refractive index focusing lens 22 focuses the single collimated, multiplexed, polychromatic optical output beam 30', and then transmits the resulting single multiplexed, polychromatic optical output beam 30 to the output fiber coupling device 24 where it becomes incident upon the single optical output fiber 26. The single multiplexed, polychromatic optical output beam 30 is then coupled into the single optical output fiber 26 for transmission therethrough.

At this point it should be noted that the single multiplexed, polychromatic optical output beam 30 is insured of being directed to the single optical output fiber 22 in a very efficient manner (i.e., with very low insertion losses and negligible channel crosstalk) by virtue of the enhanced imaging of both the input optical beams 28 and output optical beam 30 within the multiplexing device 10 through the use of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22. This enhanced imaging of both the input optical beams 28 and output optical beam 30 within the multiplexing device 10 is a direct result of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 being formed of a high index of refraction glass material.

The use of a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 insures that the multiplexing device 10 operates in a very efficient manner (i.e., with very low insertion losses and negligible

PAGE 19/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

channel crosstalk) due to the fact that a large difference exists between the high index of refraction of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 and the much lower index of refraction of the air spaces adjacent to these lenses 16, 22. This large difference between the high index of refraction of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 and the much lower index of refraction of the adjacent air spaces allows for the highly efficient collimation and focusing of the input optical beams 28 and output optical beam 30 by the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22, respectively, while simultaneously minimizing the amount of wavelength distortion that is introduced into the optical system of the multiplexing device 10 by these lenses 16, 22. Furthermore, this large difference between the high index of refraction of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 and the much lower index of refraction of the adjacent air spaces is much greater than can be achieved using lenses formed of standard optical glasses because standard optical glasses have index of refraction values that are much lower than high index of refraction glass materials. Thus, the efficiencies that are achieved by using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 are greater than can be achieved using lenses formed of standard optical glasses.

Examples of high index of refraction glass materials which can be used to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex

PAGE 20/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

homogeneous refractive index focusing lens 22 include SF59 (manufactured by Schott Glass Technologies, Inc. with n = 1.896 @ 1550 nm), PBH71 (manufactured by Ohara Corporation with n = 1.870 @ 1550 nm), LAH78 (manufactured by Ohara Corporation with n = 1.860 @ 1550 nm), and any of a number of other appropriate high index of refraction glass materials that efficiently transmit optical beams in the infrared (IR) region of the electromagnetic spectrum, since this is the region where the power loss (attenuation) and dispersion of silica-based optical fibers is very low. In fact, most WDM devices are used in the window of 1530-1610 nm, which is the range over which erbium-doped fiber amplifiers (EDFAs) operate and optical fibers have low loss. This 1530-1610 nm region is often called the "third window" for optical fibers. Similarly, however, some WDM devices are also used in the so-called "second window" for optical fibers (i.e., typically within the window of 1300-1330 nm) where optical fibers have very low dispersion and low loss. Consequently, most prior art WDM devices use standard optical glasses that transmit efficiently in these IR regions. For example, standard optical glasses such as FK3 (manufactured by Schott Glass Technologies, Inc. with n = 1.450 @ 1550 nm), BK7 (manufactured by Schott Glass Technologies, Inc. with n = 1.501 @ 1550 nm), K5 (manufactured by Schott Glass Technologies, Inc. with n = 1.506 @ 1550 nm), and Gradium have optical transmission efficiencies of 97-99% for one-inch material thicknesses in these IR regions. This level of transmission efficiency is generally adequate, but, as previously mentioned, there are cost considerations associated with the use of these materials for lenses in WDM devices (i.e., increased component costs for WDM devices requiring multiple lenses formed of standard optical glass materials, and increased fabrication costs for gradient refractive index lenses). Furthermore, all of these standard optical glasses have

PA E 21/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

index of refraction values (i.e., typically $n \approx 1.5$ @ 1550 nm) that are much lower than the index of refraction values of high index of refraction glass materials (i.e., typically $n \approx 1.9$ @ 1550 nm).

An additional benefit to using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 is that the use of a high index of refraction glass material allows the collimating lens 16 and the focusing lens 22 to be a plano-convex singlet instead of a bi-convex singlet, doublet, or even higher number lens configuration. That is, the collimating/focusing power of only one curved surface on the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 is sufficient to provide essentially diffraction-limited collimating/focusing. It should be noted, however, that the above does not preclude the collimating lens 16 and the focusing lens 22 from being a bi-convex homogeneous refractive index collimating/focusing singlet, doublet, or even higher number lens configuration. To the contrary, if the collimating lens 16 or the focusing lens 22 is a bi-convex homogeneous refractive index collimating/focusing singlet, doublet, or even higher number lens configuration, the imaging of both the input optical beams 28 and output optical beam 30 within the multiplexing device 10 is improved even more, as will be discussed in more detail below.

A further benefit to using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 is that the high index of refraction glass material can be used to lessen, and possibly even eliminate, aberrations caused by

PAGE 22/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

the spherical nature of the lenses 16, 22. These aberrations are lessened because the much greater refractive index of the high index glass material allows the radius of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 to be greatly increased (i.e., the lenses have much less curvature), thereby resulting in much less spherical and other aberrations. For example, if the plano-convex homogeneous refractive index collimating lens 16 or the plano-convex homogeneous refractive index focusing lens 22 were to be fabricated of SF59 (manufactured by Schott Glass Technologies, Inc. with n = 1.896 @ 1550 nm), then, everything else remaining the same, the required radius of the lenses 16, 22 would be much greater (i.e., the lenses would have less curvature or be less steep) than if the lenses 16, 22 were to be fabricated of a typical optical glass such as FK3 (manufactured by Schott Glass Technologies, Inc. with n = 1.450 @ 1550 nm) due to the large difference between the refractive index values of SF59 and air (i.e., 1.896 - 1.0 = 0.896) in comparison to the lesser difference between the refractive index values of FK3 and air (i.e., 1.450 - 1.0 = 0.450). That is, the difference between the refractive index values of SF59 and air is almost two times greater than the difference between the refractive index values of FK3 and air. Accordingly, the radius of the lenses 16, 22 if fabricated of SF59 is allowed to be almost two times greater than the radius of the lenses 16, 22 if fabricated of FK3. Further, aberrations caused by the spherical nature of the lenses 16, 22 are also typically reduced by this same factor (i.e., by approximately 2X).

The above-described ability to decrease the level of aberrations in the multiplexing device 10 by using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the

PAGE 23/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

plano-convex homogeneous refractive index focusing lens 22 is very significant. This discovery insures that the use of high index of refraction glass materials will result in a very large amount (or degree) of lens design freedom. The high index of refraction can be used either to make the curvature of a lens less steep, or to simplify the number and/or complexity of the lenses that are used in a WDM device.

At this point it should be noted that the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22, as well as any other homogeneous refractive index collimating/focusing lens described herein as being used in WDM devices in accordance with the present invention, may be spherical or aspherical in shape. Although spherical lenses are more common than aspherical lenses, mainly due to the fact that they are easier to manufacture, the performance of a WDM device may be further improved by using an aspherical homogeneous refractive index collimating/focusing lens instead of a spherical homogeneous refractive index collimating/focusing lens. That is, the curvature at the edges of an aspherical homogeneous refractive index collimating/focusing lens is less steep than the curvature at the edges of a spherical homogeneous refractive index collimating/focusing lens, thereby resulting in even further reductions in the level of spherical aberrations in a WDM device incorporating such an aspherical homogeneous refractive index collimating/focusing lens.

At this point it should also be noted that the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22, as well as any other homogeneous refractive index collimating/focusing lens described herein as being used in WDM devices in accordance with the present invention, is

PAGE 24/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

typically coated with an anti-reflection material due to the high index of refraction of the glass material.

At this point it should be noted that the plurality of optical input fibers 12 could be replaced in the multiplexing device 10 by a corresponding plurality of laser diodes 32 secured within a coupling device 34, such as shown in Figure 2a. The coupling device 34 performs a similar function to the input fiber coupling device 14, that being to precisely group the plurality of laser diodes 32 into a one-dimensional input array. The plurality of laser diodes 32 are used in place of the plurality of optical input fibers 12 to transmit the plurality of monochromatic optical input beams 28 to the multiplexing device 10. The array of laser diodes 32 may operate alone, or may be used with appropriate focusing lenses to provide the best coupling and the lowest amount of signal loss and channel crosstalk.

At this point it should be noted that the multiplexing device 10, as well as all of the multiplexing devices described herein, may be operated in a converse configuration as a demultiplexing device 40, such as shown in Figure 3. The demultiplexing device 40 is physically identical to the multiplexing device 10, and is therefore numerically identified as such. However, the demultiplexing device 40 is functionally opposite to the multiplexing device 10, wherein the plano-convex homogeneous refractive index collimating lens 16 now functions as a plano-convex homogeneous refractive index focusing lens 16 and the plano-convex homogeneous refractive index focusing lens 22 now functions as a plano-convex homogeneous refractive index collimating lens 22. That is, a single multiplexed, polychromatic optical input beam 42 is transmitted from the single optical fiber 26, and a plurality of monochromatic optical output beams 44 are transmitted to the plurality of optical fibers 12,

PAGE 25/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

wherein each one of the plurality of monochromatic optical output beams 44 is transmitted to a corresponding one of the plurality of optical fibers 12. The single multiplexed, polychromatic optical input beam 42 is simultaneously carrying a plurality of channels of data, each at a unique wavelength which is preferably, but not required to be, within the infrared (IR) region of the electromagnetic spectrum. The plurality of monochromatic optical output beams 44 are each carrying a single channel of data at a corresponding one of the unique wavelengths of the single multiplexed, polychromatic optical input beam 42. In this case, the single multiplexed, polychromatic optical input beam 42 is separated into the plurality of monochromatic optical output beams 44 through the combined operation of the plano-convex homogeneous refractive index collimating lens 22, the transmissive diffraction grating 20, and the plano-convex homogeneous refractive index focusing lens 16. That is, the plano-convex homogeneous refractive index collimating lens 22 collimates the single multiplexed, polychromatic optical input beam 42 to provide a single collimated, multiplexed, polychromatic optical input beam 42'. The transmissive diffraction grating 20 spatially separates the single collimated, multiplexed, polychromatic optical input beam 42' into a plurality of collimated, monochromatic optical input beams 44'', which are reflected off the reflecting surface 18a to provide a plurality of reflected, collimated, monochromatic optical input beams 44'. The plano-convex homogeneous refractive index focusing lens 16 focuses the plurality of reflected, collimated, monochromatic optical input beams 44' to provide the plurality of monochromatic optical output beams 44. Thus, the plano-convex homogeneous refractive index collimating lens 22, the transmissive diffraction grating 20, and a plano-convex homogeneous refractive index focusing lens 16 operate to perform a demultiplexing

PAGE 26/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

function. Of course, in this case, the incident angle, α, and the diffraction angle, β, are reversed in comparison to the multiplexing device 10 shown in Figure 1a, and the reflecting angle, θ, is equal to one-half of the diffraction angle, β.

At this point it should be noted that the plurality of optical fibers 12 could be replaced in the demultiplexing device 40 by a corresponding plurality of photodetectors 36 secured within a coupling device 38, such as shown in Figure 2b. The coupling device 38 performs a similar function to the fiber coupling device 14, that being to precisely group the plurality of photodetectors 36 into a one-dimensional output array. The plurality of photodetectors 36 are used in place of the plurality of optical fibers 12 to receive the plurality of monochromatic optical output beams 44 from the demultiplexing device 40. The array of photodetectors 36 may operate alone, or may be used with appropriate focusing lenses to provide the best coupling and the lowest amount of signal loss and channel crosstalk.

Referring to Figure 4, there is shown a side view of an alternate embodiment of a wavelength division multiplexing device 50 in accordance with the present invention. The multiplexing device 50 is physically identical to the multiplexing device 10, except for the addition of a first homogeneous refractive index boot lens 52 between the input fiber coupling device 14 and the plano-convex homogeneous refractive index collimating lens 16, a second homogeneous refractive index boot lens 54 and an optional spacer 21 between the plano-convex homogeneous refractive index collimating lens 16 and the reflecting element 18, a third homogeneous refractive index boot lens 56 between the transmissive diffraction grating 20 and the plano-convex homogeneous refractive index focusing lens 22, and a fourth homogeneous refractive index boot lens 58

PAGE 27/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

between the plano-convex homogeneous refractive index focusing lens 22 and the output fiber coupling device 24. The first homogeneous refractive index boot lens 52, the second homogeneous refractive index boot lens 54, the third homogeneous refractive index boot lens 56, and the fourth homogeneous refractive index boot lens 58 are preferably fabricated of, for example, fused silica (manufactured by Schott Glass Technologies, Inc. with n = 1.444 @ 1550 nm), although numerous other low index of refraction optical glass materials may also be used. The optional spacer 21 is also preferably fabricated of a low index of refraction optical glass material such as, for example, fused silica, and is used to maintain the spacing and alignment between the various parts of the multiplexing device 50.

The first homogeneous refractive index boot lens 52 has a planar front surface 52a for mating with the input fiber coupling device 14 and the associated secured optical input fibers 12. The input fiber coupling device 14 and the secured optical input fibers 12 may be either abutted against the planar front surface 52a or affixed to the planar front surface 52a using optical cement or some other optically transparent bonding technique, depending upon system mobility requirements and optical beam alignment and loss considerations.

The first homogeneous refractive index boot lens 52 also has a planar back surface 52b for mating with a planar front surface 16a of the plano-convex homogeneous refractive index collimating lens 16. The planar back surface 52b of the first homogeneous refractive index boot lens 52 is typically joined or affixed to the planar front surface 16a of the plano-convex homogeneous refractive index collimating lens 16 using optical cement or some other optically transparent bonding technique.

The second homogeneous refractive index boot lens 54 has a concave front surface 54a for mating with a convex

PAGE 28/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

back surface 16b of the plano-convex homogeneous refractive index collimating lens 16. The concave front surface 54a of the second homogeneous refractive index boot lens 54 is typically joined or affixed to the convex back surface 16b of the plano-convex homogeneous refractive index collimating lens 16 using optical cement or some other optically transparent bonding technique.

The second homogeneous refractive index boot lens 54 also has a planar back surface 54b for mating with a planar front surface 21a of the optional spacer 21. The planar back surface 54b of the second homogeneous refractive index boot lens 54 is typically joined or affixed to the planar front surface 21a of the optional spacer 21 using optical cement or some other optically transparent bonding technique.

The optional spacer 21 is typically has a planar back surface 21b for typically mating with a planar interface surface 18b of the reflecting element 18. The planar back surface 21b of the optional spacer 21 is typically joined or affixed to the planar interface surface 18b of the reflecting element 18 using optical cement or some other optically transparent bonding technique.

At this point it should be noted that, instead of the optional spacer 21, the planar back surface 54b of the second homogeneous refractive index boot lens 54 could be extended to the planar interface surface 18b of the reflecting element 18 if such additional spacing is beneficially required or desired.

Similar to the first homogeneous refractive index boot lens 52, the fourth homogeneous refractive index boot lens 58 has a planar front surface 58a for mating with the output fiber coupling device 24 and the associated secured optical output fiber 26. The output fiber coupling device 24 and the secured optical output fiber 26 may be either abutted against the planar front surface 58a or affixed to

PA E 29/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

the planar front surface 58a using optical cement or some other optically transparent bonding technique, depending upon system mobility requirements and optical beam alignment and loss considerations.

The fourth homogeneous refractive index boot lens 58 also has a planar back surface 58b for mating with a planar front surface 22a of the plano-convex homogeneous refractive index focusing lens 22. The planar back surface 58b of the fourth homogeneous refractive index boot lens 58 is typically joined or affixed to the planar front surface 22a of the plano-convex homogeneous refractive index focusing lens 22 using optical cement or some other optically transparent bonding technique.

Similar to the second homogeneous refractive index boot lens 54, the third homogeneous refractive index boot lens 56 has a concave front surface 56a for mating with a convex back surface 22b of the plano-convex homogeneous refractive index focusing lens 22. The concave front surface 56a of the third homogeneous refractive index boot lens 56 is typically joined or affixed to the planar back surface 22b of the plano-convex homogeneous refractive index focusing lens 22 using optical cement or some other optically transparent bonding technique.

The third homogeneous refractive index boot lens 56 also has a planar back surface 56b for typically mating with a planar front surface 20a of the transmissive diffraction grating 20. The planar back surface 56b of the third homogeneous refractive index boot lens 56 is typically joined or affixed to the planar front surface 20a of the transmissive diffraction grating 20 using optical cement or some other optically transparent bonding technique.

The transmissive diffraction grating 20 typically has a planar back surface 20b for typically mating with the planar interface surface 18b of the reflecting element 18.

PAGE 30/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

The planar back surface 20b of the transmissive diffraction grating 20 is typically joined or affixed to the planar interface surface 18b of the reflecting element 18 using optical cement or some other optically transparent bonding technique.

At this point it should be noted that, as with the multiplexing device 10, the transmissive diffraction grating 20 can be formed directly on the planar interface surface 18b of the reflecting element 18, thereby avoiding the joining or affixing of the transmissive diffraction grating 20 to the reflecting element 18 or the third homogeneous refractive index boot lens 56, and also avoiding the need for the optional spacer 21. Alternatively, the transmissive diffraction grating 20 can be formed directly on the planar back surface 56b of the third homogeneous refractive index boot lens 56, thereby avoiding the joining or affixing of the transmissive diffraction grating 20 to the reflecting element 18 or the third homogeneous refractive index boot lens 56, and also avoiding the need for the optional spacer 21.

In any of the above-described cases, the transmissive diffraction grating 20 is integrated along with at least the reflecting element 18, the plano-convex homogeneous refractive index collimating lens 16, the plano-convex homogeneous refractive index focusing lens 22, and the homogeneous refractive index boot lenses 52, 54, 56, and 58, to form a compact, rigid, and environmentally and thermally stable multiplexing device 50. The integrated nature of this multiplexing device 50 is particularly useful for maintaining component alignment, which provides long-term performance in contrast to some non-integrated air-spaced devices that characteristically degrade in alignment and therefore performance over time.

The multiplexing device 50 is functionally identical to the multiplexing device 10, except for a slight decrease

PAGE 31/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * VR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

in optical beam transmission efficiency due to the addition of the homogeneous refractive index boot lenses 52, 54, 56, and 58, and the optional spacer 21. However, even with this slight decrease in optical beam transmission efficiency, the optical performance of the multiplexing device 50 is still exceptional due to the use of a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22. That is, as previously described, the high index of refraction glass material can be used to lessen, and possibly even eliminate, aberrations caused by the spherical nature of the lenses 16, 22. And these aberrations are still lessened despite the addition of the homogeneous refractive index boot lenses 52, 54, 56, and 58, and the optional spacer 21. For example, if the homogeneous refractive index boot lenses 52, 54, 56, and 58 and the optional spacer 21 were to be fabricated of a first type of standard optical glass (e.g., fused silica manufactured by Schott Glass Technologies, Inc. with n = 1.444 @ 1550 nm) and if the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 were to be fabricated of SF59 (manufactured by Schott Glass Technologies, Inc. with n = 1.896 @ 1550 nm), then, everything else remaining the same, the required radius of the lenses 16, 22 would be much greater (i.e., the lenses would have less curvature or be less steep) than if the lenses 16, 22 were to be fabricated of a second type of standard optical glass (e.g., BK7 manufactured by Schott Glass Technologies, Inc. with n = 1.501 @ 1550 nm) due to the large difference between the refractive index values of SF59 and fused silica (i.e., 1.896 - 1.444 = 0.452) in comparison to the lesser difference between the refractive index values of BK7 and fused silica (i.e., 1.501 - 1.444

PAGE 32/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

= 0.057). That is, the difference between the refractive index values of SF59 and fused silica is 7.93 times greater than the difference between the refractive index values of BK7 and fused silica. Accordingly, the radius of the lenses 16, 22 if fabricated of SF59 is allowed to be 7.93 times greater than the radius of the lenses 16, 22 if fabricated of BK7. Further, aberrations caused by the spherical nature of the lenses 16, 22 are also typically reduced by this same factor (i.e., by 7.93 times).

Referring to Figure 5, there is shown a side view of an alternate embodiment of a wavelength division multiplexing device 60 in accordance with the present invention. The multiplexing device 60 is physically identical to the multiplexing device 50, except that the first homogeneous refractive index boot lens 52 has been removed and the planar front surface 16'a of the plano-convex homogeneous refractive index collimating lens 16' has been extended so as to allow the input fiber coupling device 14 and the secured optical input fibers 12 to be either abutted against the planar front surface 16'a or affixed to the planar front surface 16'a using optical cement or some other optically transparent bonding technique, depending upon system mobility requirements and optical beam alignment and loss considerations, and that the fourth homogeneous refractive index boot lens 58 has been removed and the planar front surface 22'a of the plano-convex homogeneous refractive index focusing lens 22' has been extended so as to allow the output fiber coupling device 24 and the secured optical output fiber 26 to be either abutted against the planar front surface 22'a or affixed to the planar front surface 22'a using optical cement or some other optically transparent bonding technique, depending upon system mobility requirements and optical beam alignment and loss considerations. Similar to the multiplexing device 50, the integrated nature of the

PAGE 33/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

multiplexing device 60 is particularly useful for maintaining component alignment, which provides long-term performance in contrast to some non-integrated air-spaced devices that characteristically degrade in alignment and therefore performance over time. The multiplexing device 60 is functionally identical to the multiplexing device 50, except for a slight increase in optical beam transmission efficiency due to the removal of the first homogeneous refractive index boot lens 52 and the fourth homogeneous refractive index boot lens 58.

At this point it should be noted that the plano-convex homogeneous refractive index collimating lens 16 and/or the plano-convex homogeneous refractive index focusing lens 22, as shown in the multiplexing device 10 of Figure 1, may be replaced by a convex-plano homogeneous refractive index collimating lens 17 and/or a convex-plano homogeneous refractive index focusing lens 23, respectively, to form an alternate embodiment of a wavelength division multiplexing device 70 in accordance with the present invention as shown in Figure 6. The multiplexing device 70 of Figure 6 realizes the above-described benefits of using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 in the multiplexing device 10 of Figure 1. That is, the above-described benefits of using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22 in multiplexing device 10 of Figure 1 are also realized when using a high index of refraction glass material to form the convex-plano homogeneous refractive index collimating lens 17 and/or the convex-plano homogeneous refractive index focusing lens 23 in multiplexing device 70

PAGE 34/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

of Figure 6. The multiplexing device 70 is functionally identical to the multiplexing device 10.

At this point it should be noted, similar to the multiplexing device 50 of Figure 4, homogeneous refractive index boot lenses can be added to the multiplexing device 70 of Figure 6 to form an alternate embodiment of a wavelength division multiplexing device 80 in accordance with the present invention as shown in Figure 7. The multiplexing device 80 of Figure 7 realizes the above-described benefits of using homogeneous refractive index boot lenses in the multiplexing device 50 of Figure 4. That is, the above-described benefits of using the first homogeneous refractive index boot lens 52, the second homogeneous refractive index boot lens 54, the third homogeneous refractive index boot lens 56, and the fourth homogeneous refractive index boot lens 58 in multiplexing device 50 of Figure 4 are also realized when using a first homogeneous refractive index boot lens 53, a second homogeneous refractive index boot lens 55, a third homogeneous refractive index boot lens 57, and a fourth homogeneous refractive index boot lens 59 in multiplexing device 80 of Figure 7. As with all of the previously described embodiments, the transmissive diffraction grating 20 can be formed using a separate material, and this material can then be joined or affixed to the planar back surface 57b of the homogeneous refractive index boot lens 57 and to the planar interface surface 18b of the reflecting element 18 using optical cement or some other optically transparent bonding technique. Alternatively, the transmissive diffraction grating 20 can be formed directly on the planar back surface 57b of the homogeneous refractive index boot lens 57 or on the planar interface surface 18b of the reflecting element 18, thereby avoiding the joining or affixing of the transmissive diffraction grating 20 to the planar back surface 57b of the

PAGE 35/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

homogeneous refractive index boot lens 57 and to the planar interface surface 18b of the reflecting element 18. Similar to the multiplexing device 50, the integrated nature of the multiplexing device 80 is particularly useful for maintaining component alignment, which provides long-term performance in contrast to some non-integrated air-spaced devices that characteristically degrade in alignment and therefore performance over time. The multiplexing device 80 is functionally identical to the multiplexing device 50.

At this point it should be noted that the second homogeneous refractive index boot lens 55 and the third homogeneous refractive index boot lens 57 can be removed from the multiplexing device 80 of Figure 7, and the back surface 17'b of the convex-plano homogeneous refractive index collimating lens 17' can be extended out to the optional spacer 21 and the back surface 23'b of the convex-plano homogeneous refractive index focusing lens 23' can be extended out to the transmissive diffraction grating 20, respectively, to form an alternate embodiment of a wavelength division multiplexing device 90 in accordance with the present invention as shown in Figure 8. As with all of the previously described embodiments, the transmissive diffraction grating 20 can be formed using a separate material, and this material can then be joined or affixed to the planar back surface 23'b of the convex-plano homogeneous refractive index focusing lens 23' and to the planar interface surface 18b of the reflecting element 18 using optical cement or some other optically transparent bonding technique. Alternatively, the transmissive diffraction grating 20 can be formed directly on the planar back surface 23'b of the convex-plano homogeneous refractive index focusing lens 23' or on the planar interface surface 18b of the reflecting element 18, thereby avoiding the joining or affixing of the transmissive

PAGE 36/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

diffraction grating 20 to the planar back surface 23'b of the convex-plano homogeneous refractive index focusing lens 23' and to the planar interface surface 18b of the reflecting element 18. Similar to the multiplexing device 60, the integrated nature of the multiplexing device 90 is particularly useful for maintaining component alignment, which provides long-term performance in contrast to some non-integrated air-spaced devices that characteristically degrade in alignment and therefore performance over time. The multiplexing device 90 is functionally identical to the multiplexing device 60.

At this point it should be noted that any of the homogeneous refractive index boot lenses 52, 54, 56, and 58 may be removed from the multiplexing device 50, either of the homogeneous refractive index boot lenses 54, 56 may be removed from the multiplexing device 60, any of the homogeneous refractive index boot lenses 53, 55, 57, and 59 may be removed from the multiplexing device 80, and either of the homogeneous refractive index boot lenses 53, 59 may be removed from the multiplexing device 90, in order to create additional alternate embodiments (not shown) while still retaining the above-described benefits of using a high index of refraction glass material to form the plano-convex homogeneous refractive index collimating lens 16, the convex-plano homogeneous refractive index collimating lens 17, the plano-convex homogeneous refractive index focusing lens 22, and the convex-plano homogeneous refractive index focusing lens 23.

Referring to Figure 9, there is shown a side view of an alternate embodiment of a wavelength division multiplexing device 100 in accordance with the present invention. The multiplexing device 100 is physically identical to the multiplexing device 10, except that the plano-convex homogeneous refractive index collimating lens 16 has been replaced by a bi-convex homogeneous refractive

PAGE 37/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

index collimating lens 72 and that the plano-convex homogeneous refractive index focusing lens 22 has been replaced by a bi-convex homogeneous refractive index focusing lens 74 so as to further enhance the imaging of both the input optical beams 28 and output optical beam 30 within the multiplexing device 100. That is, the additional curved surfaces of the bi-convex homogeneous refractive index collimating lens 72 and the bi-convex homogeneous refractive index focusing lens 74 provides additional imaging capability, thereby increasing the fiber coupling efficiency (FCE) of the multiplexing device 100. In contrast to a measure of insertion loss, the FCE of a WDM device expresses the efficiency of only the optical system of the WDM device for each data channel, without taking into account the efficiency of the diffraction grating. Comparatively, the use of the bi-convex homogeneous refractive index collimating lens 72 and the bi-convex homogeneous refractive index focusing lens 74 instead of the plano-convex homogeneous refractive index collimating lens 16 and the plano-convex homogeneous refractive index focusing lens 22, respectively, typically results in an increase in the FCE of approximately 1% for the configuration of WDM devices shown in Figures 1 and 9. Thus, a trade-off must be made between a small increase in the FCE and the additional cost associated with fabricating lenses having an additional curved surface. Of course, further increases in the FCE can typically be achieved using doublet, triplet, or even higher number lens configurations.

Referring to Figure 10, there is shown a side view of an alternate embodiment of a wavelength division multiplexing device 110 in accordance with the present invention. The multiplexing device 110 is physically identical to the multiplexing device 50, except that the plano-convex homogeneous refractive index collimating lens

PAGE 38/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

16 has been replaced by a bi-convex homogeneous refractive index collimating lens 72, the first homogeneous refractive index boot lens 52 has been replaced by the first homogeneous refractive index boot lens 53, the plano-convex homogeneous refractive index focusing lens 22 has been replaced by a bi-convex homogeneous refractive index focusing lens 74, and the fourth homogeneous refractive index boot lens 58 has been replaced by the fourth homogeneous refractive index boot lens 59. As with the multiplexing device 100, the replacement of the plano-convex homogeneous refractive index collimating lens 16 with the bi-convex homogeneous refractive index collimating lens 72 and the replacement of the plano-convex homogeneous refractive index focusing lens 22 with the bi-convex homogeneous refractive index focusing lens 74 in the multiplexing device 110 has been done to further enhance the imaging of both the input optical beams 28 and output optical beam 30 within the multiplexing device 80. The first homogeneous refractive index boot lens 52 has been replaced with the first homogeneous refractive index boot lens 53 because the first homogeneous refractive index boot lens 53 has a concave back surface 53b for mating with the convex front surface 72a of the bi-convex homogeneous refractive index collimating lens 72. Similarly, the fourth homogeneous refractive index boot lens 58 has been replaced with the fourth homogeneous refractive index boot lens 59 because the fourth homogeneous refractive index boot lens 59 has a concave back surface 59b for mating with the convex front surface 74a of the bi-convex homogeneous refractive index focusing lens 74.

At this point it should be noted that, as with the multiplexing device 50, any of the homogeneous refractive index boot lenses 53, 54, 56, and 59 may be removed from the multiplexing device 110 in order to create additional alternate embodiments (not shown) while still retaining the

PAGE 39/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

above-described benefits of using a high index of refraction glass material to form the bi-convex homogeneous refractive index collimating lens 72 and the bi-convex homogeneous refractive index focusing lens 74. Also, the bi-convex homogeneous refractive index collimating lens 72 and/or the bi-convex homogeneous refractive index focusing lens 74 can be replaced with a plano-convex homogeneous refractive index lens(es), or a homogeneous refractive index collimating/focusing doublet, triplet, or even higher number lens configuration, in the multiplexing device 110 in accordance with the practices described above.

Referring to Figure 11, there is shown a side view of an alternate embodiment of a wavelength division multiplexing device 120 in accordance with the present invention. The multiplexing device 120 differs from the previously described embodiments by having an in-line geometry rather than the folded geometry of the previously described embodiments. This in-line geometry is achieved through the use of a dual reflecting element 92, which has a first reflecting surface 92a for reflecting the plurality of collimated, monochromatic optical input beams 28' and a second reflecting surface 92b for reflecting the plurality of reflected, collimated, monochromatic optical input beams 28''. Note that, in contrast to the previously described embodiments, the multiplexing device 120 does not require the optional spacer 21 to maintain the spacing and alignment between the various parts of the multiplexing device 120. Otherwise, the multiplexing device 120 is functionally identical to and utilizes all of the components used in the multiplexing device 110, except of course the reflecting element 18.

At this point it should be noted that, as with the multiplexing device 50 and the multiplexing device 80, any of the homogeneous refractive index boot lenses 53, 54, 56, and 59 may be removed from the multiplexing device 120 in

PAGE 40/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

order to create additional alternate embodiments (not shown) while still retaining the above-described benefits of using a high index of refraction glass material to form the bi-convex homogeneous refractive index collimating lens 72 and the bi-convex homogeneous refractive index focusing lens 74. Also, the bi-convex homogeneous refractive index collimating lens 72 and/or the bi-convex homogeneous refractive index focusing lens 74 can be replaced with a plano-convex homogeneous refractive index lens(es), or a homogeneous refractive index collimating/focusing doublet, triplet, or even higher number lens configuration, in the multiplexing device 120 in accordance with the practices described above. The benefits and detriments associated with using these substitute/additional components are applicable to the multiplexing device 120 as would be the case with the previously described embodiments. Of course, the most significant benefits come from the use of high index of refraction glass materials for the lenses. That is, regardless of embodiment, the use of high index of refraction glass materials for lenses in WDM devices yields increased device performance, as well as reduced device cost, complexity, and manufacturing risk. Simply said, the use of high index of refraction glass lenses allows for the construction of a family of simple, low cost, yet very powerful WDM devices, particularly for use in DWDM (i.e., high channel number) applications.

The present invention is not to be limited in scope by the specific embodiments described herein. Indeed, various modifications of the present invention, in addition to those described herein, will be apparent to those of skill in the art from the foregoing description and accompanying drawings. Thus, such modifications are intended to fall within the scope of the appended claims.

PAGE 41/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

CLAIMS

WHAT IS CLAIMED IS:

1. A wavelength division multiplexing device comprising:

a homogeneous refractive index collimating lens for collimating a plurality of monochromatic optical beams;

a diffraction grating for combining the plurality of collimated, monochromatic optical beams into a multiplexed, polychromatic optical beam; and

a homogeneous refractive index focusing lens for focusing the multiplexed, polychromatic optical beam.

2. The device as defined in claim 1, wherein the diffraction grating is a transmissive diffraction grating.

3. The device as defined in claim 1, wherein the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens have high indexes of refraction.

4. The device as defined in claim 1, wherein the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens operate in the infrared region of the electromagnetic spectrum.

5. The device as defined in claim 1, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a plano-convex lens or a convex-plano lens.

6. The device as defined in claim 1, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a bi-convex lens.

PAGE 42/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

7. The device as defined in claim 1, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a spherical lens.

8. The device as defined in claim 1, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is an aspherical lens.

9. The device as defined in claim 1, wherein the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens are formed of a high index of refraction glass material selected from the group consisting of SF59, PBH71, LAH78, and other high index of refraction glass materials that efficiently transmit optical beams in the infrared IR region of the electromagnetic spectrum.

10. An integrated wavelength division multiplexing device comprising:

a homogeneous refractive index collimating lens for collimating a plurality of monochromatic optical beams;

a homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the plurality of collimated, monochromatic optical beams from the homogeneous refractive index collimating lens, the homogeneous refractive index boot lens having a planar exit surface; and

a diffraction grating formed at the planar exit surface of the homogeneous refractive index boot lens for combining the plurality of collimated, monochromatic optical beams into a multiplexed, polychromatic optical beam.

PAGE 43/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

11. The device as defined in claim 10, wherein the homogeneous refractive index boot lens is incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index collimating lens has the planar exit surface at which the diffraction grating is formed.

12. The device as defined in claim 10, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the plurality of monochromatic optical beams to the homogeneous refractive index collimating lens.

13. The device as defined in claim 12, wherein the second homogeneous refractive index boot lens has a planar entry surface for accepting the plurality of monochromatic optical beams from at least one optical source.

14. The device as defined in claim 10, wherein the homogeneous refractive index collimating lens has a planar entry surface for accepting the plurality of monochromatic optical beams from at least one optical source.

15. The device as defined in claim 10, wherein the diffraction grating is a transmissive diffraction grating.

16. The device as defined in claim 15, further comprising:

a transmissive element associated with the transmissive diffraction grating, the transmissive element having at least one reflective surface for reflecting the multiplexed, polychromatic optical beam.

PAGE 44/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

17. The device as defined in claim 16, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the multiplexed, polychromatic optical beam from the transmissive element; and

a homogeneous refractive index focusing lens affixed to the second homogeneous refractive index boot lens for focusing the multiplexed, polychromatic optical beam.

18. The device as defined in claim 17, wherein the second homogeneous refractive index boot lens is incorporated into the homogeneous refractive index focusing lens such that the homogeneous refractive index focusing lens is affixed to the transmissive element.

19. The device as defined in claim 17, further comprising:

a third homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the focused, multiplexed, polychromatic optical beam from the homogeneous refractive index focusing lens.

20. The device as defined in claim 19, wherein the third homogeneous refractive index boot lens has a planar exit surface for outputting the focused, multiplexed, polychromatic optical beam to at least one optical receiver.

21. The device as defined in claim 17, wherein the homogeneous refractive index focusing lens has a planar exit surface for outputting the focused, multiplexed,

PAGE 45/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

polychromatic optical beam to at least one optical receiver.

22. An integrated wavelength division multiplexing device comprising:

a homogeneous refractive index focusing lens for focusing a multiplexed, polychromatic optical beam;

a homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the multiplexed, polychromatic optical beam to the homogeneous refractive index focusing lens, the homogeneous refractive index boot lens having a planar entry surface; and

a diffraction grating formed at the planar entry surface of the homogeneous refractive index boot lens for combining a plurality of monochromatic optical beams into the multiplexed, polychromatic optical beam.

23. The device as defined in claim 22, wherein the homogeneous refractive index boot lens is incorporated into the homogeneous refractive index focusing lens such that the homogeneous refractive index focusing lens has the planar entry surface at which the diffraction grating is formed.

24. The device as defined in claim 22, wherein the diffraction grating is a transmissive diffraction grating.

25. The device as defined in claim 24, further comprising:

a transmissive element associated with the transmissive diffraction grating, the transmissive element having at least one reflective surface for reflecting the plurality of monochromatic optical beams toward the transmissive diffraction grating.

PAGE 46/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

26. The device as defined in claim 25, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the plurality of monochromatic optical beams to the transmissive element; and

a homogeneous refractive index collimating lens affixed to the second homogeneous refractive index boot lens for collimating the plurality of monochromatic optical beams prior to transmission by the second homogeneous refractive index boot lens.

27. The device as defined in claim 26, wherein the second homogeneous refractive index boot lens is incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index collimating lens is affixed to the transmissive element.

28. A wavelength division demultiplexing device comprising:

a homogeneous refractive index collimating lens for collimating a multiplexed, polychromatic optical beam;

a diffraction grating for separating the collimated, multiplexed, polychromatic optical beam into a plurality of monochromatic optical beams; and

a homogeneous refractive index focusing lens for focusing the plurality of monochromatic optical beams.

29. The device as defined in claim 28, wherein the diffraction grating is a transmissive diffraction grating.

30. The device as defined in claim 28, wherein the homogeneous refractive index collimating lens and the

PAGE 47/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPT -EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

homogeneous refractive index focusing lens have high indexes of refraction.

31. The device as defined in claim 28, wherein the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens operate in the infrared region of the electromagnetic spectrum.

32. The device as defined in claim 28, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a plano-convex lens or a convex-plano lens.

33. The device as defined in claim 28, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a bi-convex lens.

34. The device as defined in claim 28, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is a spherical lens.

35. The device as defined in claim 28, wherein at least one of the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens is an aspherical lens.

36. The device as defined in claim 28, wherein the homogeneous refractive index collimating lens and the homogeneous refractive index focusing lens are formed of a high index of refraction glass material selected from the group consisting of SF59, PBH71, LAH78, and other high index of refraction glass materials that efficiently

PAGE 48/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

transmit optical beams in the infrared IR region of the electromagnetic spectrum.

37. An integrated wavelength division demultiplexing device comprising:

a homogeneous refractive index collimating lens for collimating a multiplexed, polychromatic optical beam;

a homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the collimated, multiplexed, polychromatic optical beam from the homogeneous refractive index collimating lens, the homogeneous refractive index boot lens having a planar exit surface; and

a diffraction grating formed at the planar exit surface of the homogeneous refractive index boot lens for separating the collimated, multiplexed, polychromatic optical beam into a plurality of monochromatic optical beams.

38. The device as defined in claim 37, wherein the homogeneous refractive index boot lens is incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index collimating lens has the planar exit surface at which the diffraction grating is formed.

39. The device as defined in claim 37, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the homogeneous refractive index collimating lens for transmitting the multiplexed, polychromatic optical beam to the homogeneous refractive index collimating lens.

PAGE 49/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATI N (mm-ss):33-28

40. The device as defined in claim 39, wherein the second homogeneous refractive index boot lens has a planar entry surface for accepting the multiplexed, polychromatic optical beam from at least one optical source.

41. The device as defined in claim 37, wherein the homogeneous refractive index collimating lens has a planar entry surface for accepting the multiplexed, polychromatic optical beam from at least one optical source.

42. The device as defined in claim 37, wherein the diffraction grating is a transmissive diffraction grating.

43. The device as defined in claim 42, further comprising:

a transmissive element associated with the transmissive diffraction grating, the transmissive element having at least one reflective surface for reflecting the plurality of monochromatic optical beams.

44. The device as defined in claim 43, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the plurality of monochromatic optical beams from the transmissive element; and

a homogeneous refractive index focusing lens affixed to the second homogeneous refractive index boot lens for focusing the plurality of monochromatic optical beams.

45. The device as defined in claim 44, wherein the homogeneous refractive index boot lens is incorporated into the homogeneous refractive index focusing lens such that

PAGE 50/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

the homogeneous refractive index focusing lens is affixed to the transmissive element.

46. The device as defined in claim 44, further comprising:

a third homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the plurality of focused, monochromatic optical beams from the homogeneous refractive index focusing lens.

47. The device as defined in claim 46, wherein the third homogeneous refractive index boot lens has a planar exit surface for outputting the plurality of focused, monochromatic optical beams to at least one optical receiver.

48. The device as defined in claim 44, wherein the homogeneous refractive index focusing lens has a planar exit surface for outputting the plurality of focused, monochromatic optical beams to at least one optical receiver.

49. An integrated wavelength division demultiplexing device comprising:

a homogeneous refractive index focusing lens for focusing a plurality of monochromatic optical beams;

a homogeneous refractive index boot lens affixed to the homogeneous refractive index focusing lens for transmitting the plurality of monochromatic optical beams to the homogeneous refractive index focusing lens, the homogeneous refractive index boot lens having a planar entry surface; and

a diffraction grating formed at the planar entry surface of the homogeneous refractive index boot lens for

PAGE 51/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

separating a multiplexed, polychromatic optical beam into the plurality of monochromatic optical beams.

50. The device as defined in claim 49, wherein the homogeneous refractive index boot lens is incorporated into the homogeneous refractive index focusing lens such that the homogeneous refractive index focusing lens has the planar entry surface at which the diffraction grating is formed.

51. The device as defined in claim 49, wherein the diffraction grating is a transmissive diffraction grating.

52. The device as defined in claim 51, further comprising:

a transmissive element associated with the transmissive diffraction grating, the transmissive element having at least one reflective surface for reflecting the multiplexed, polychromatic optical beam toward the transmissive diffraction grating.

53. The device as defined in claim 52, wherein the homogeneous refractive index boot lens is a first homogeneous refractive index boot lens, the device further comprising:

a second homogeneous refractive index boot lens affixed to the transmissive element for transmitting the multiplexed, polychromatic optical beam to the transmissive element; and

a homogeneous refractive index collimating lens affixed to the second homogeneous refractive index boot lens for collimating the multiplexed, polychromatic optical beam prior to transmission by the second homogeneous refractive index boot lens.

54. The device as defined in claim 53, wherein the second homogeneous refractive index boot lens is incorporated into the homogeneous refractive index collimating lens such that the homogeneous refractive index collimating lens is affixed to the transmissive element.

PAGE 53/67 * RCVD AT 6/14/2004 3:32:56 PM [Eastern Daylight Time] * SVR:USPTO-EFXRF-3/24 * DNIS:2732099 * CSID:508 872 1492 * DURATION (mm-ss):33-28

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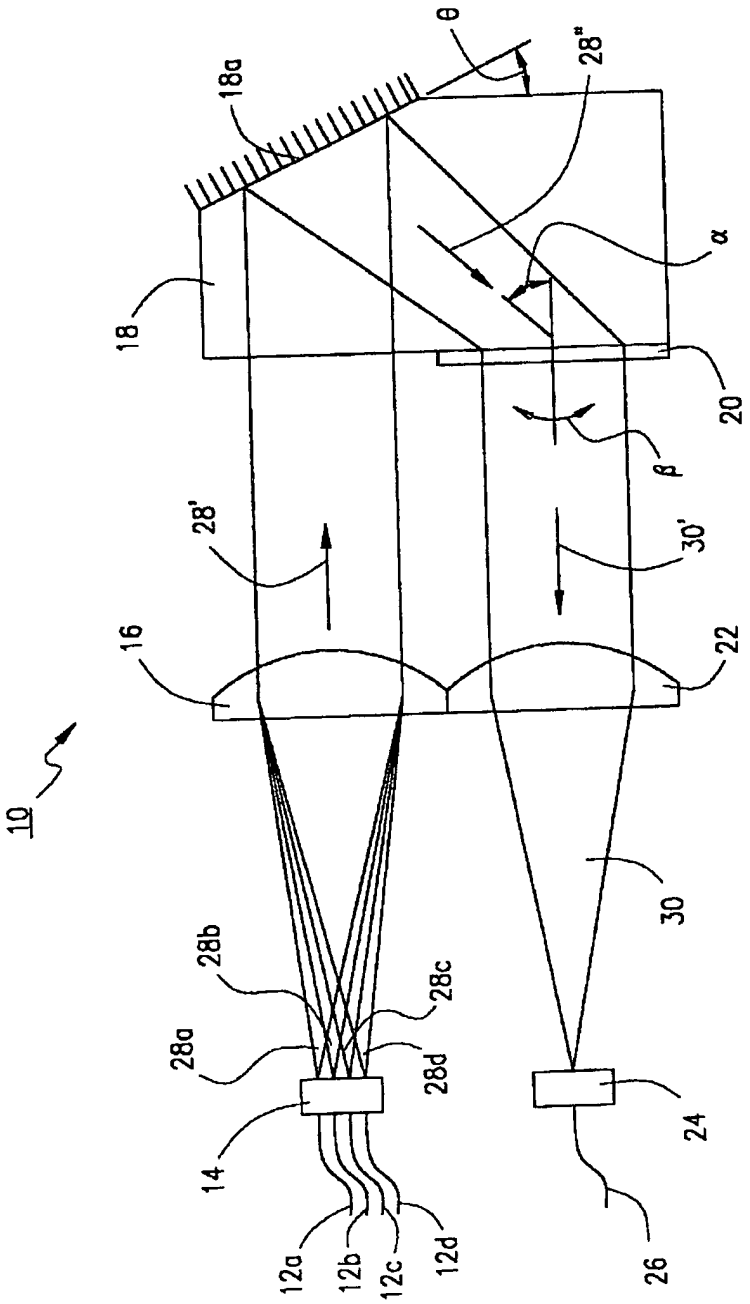


FIG. 1a

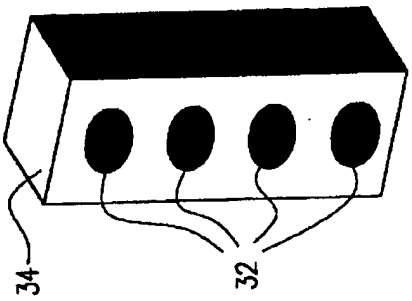


FIG. 2a

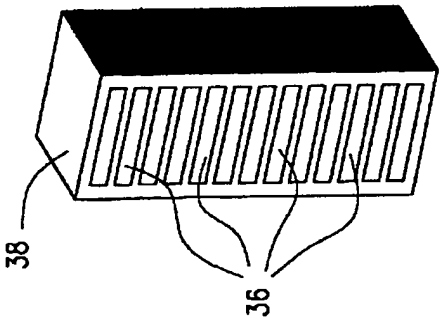


FIG. 2b

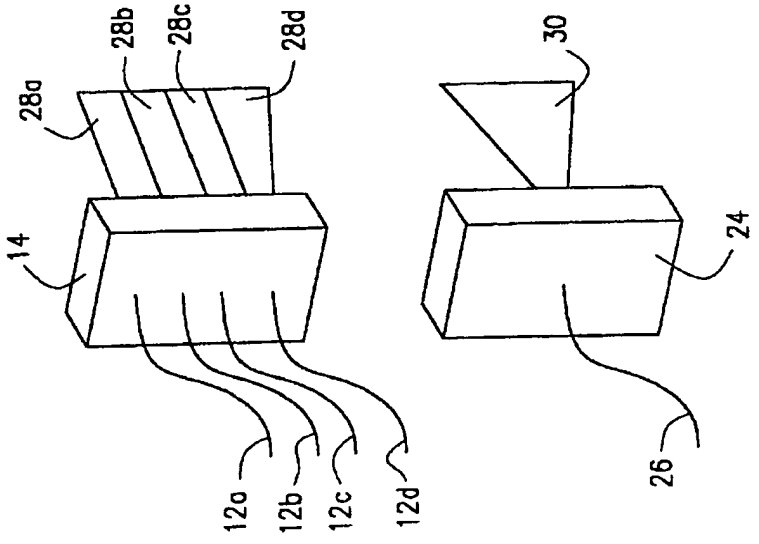


FIG. 1b

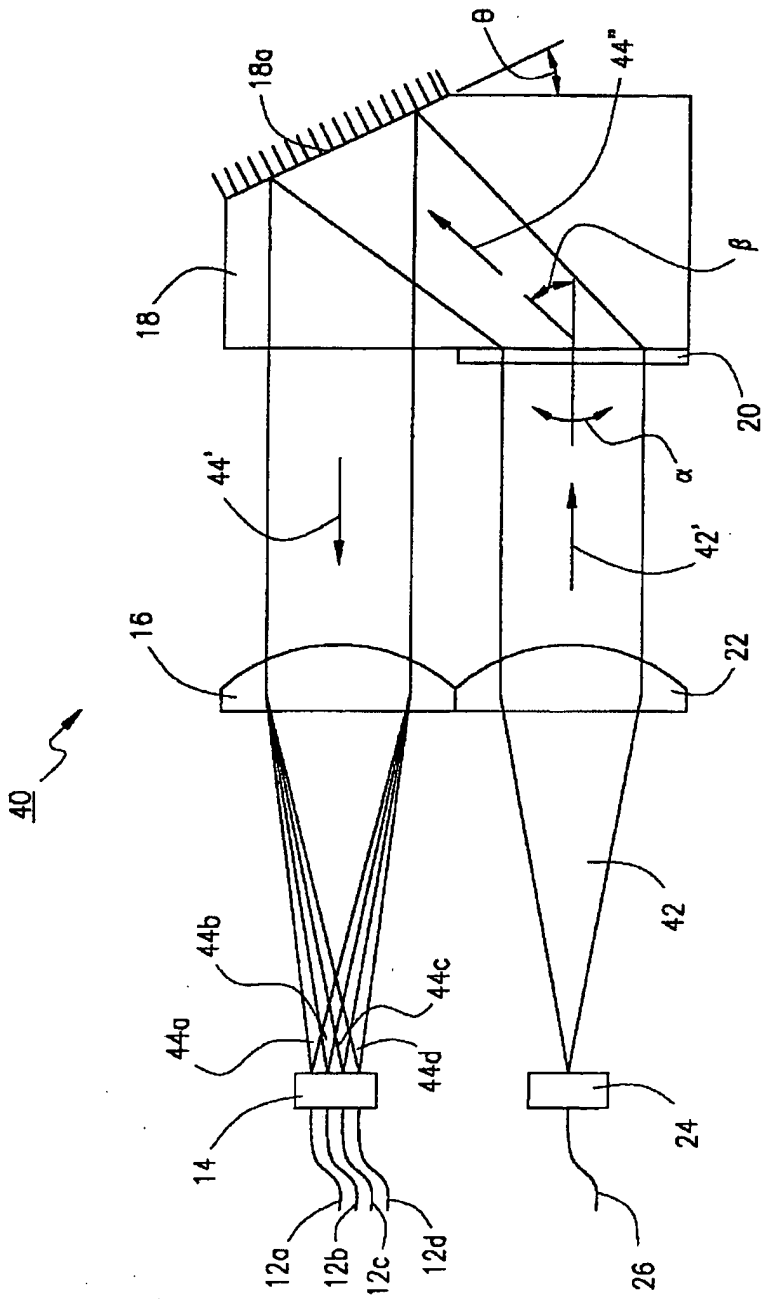

θ
18a
44"
β
18
20
α
44'
42'
16
22
40
42
44b
44c
44a
44d
14
24
12a
12b
12c
12d
26

FIG. 3

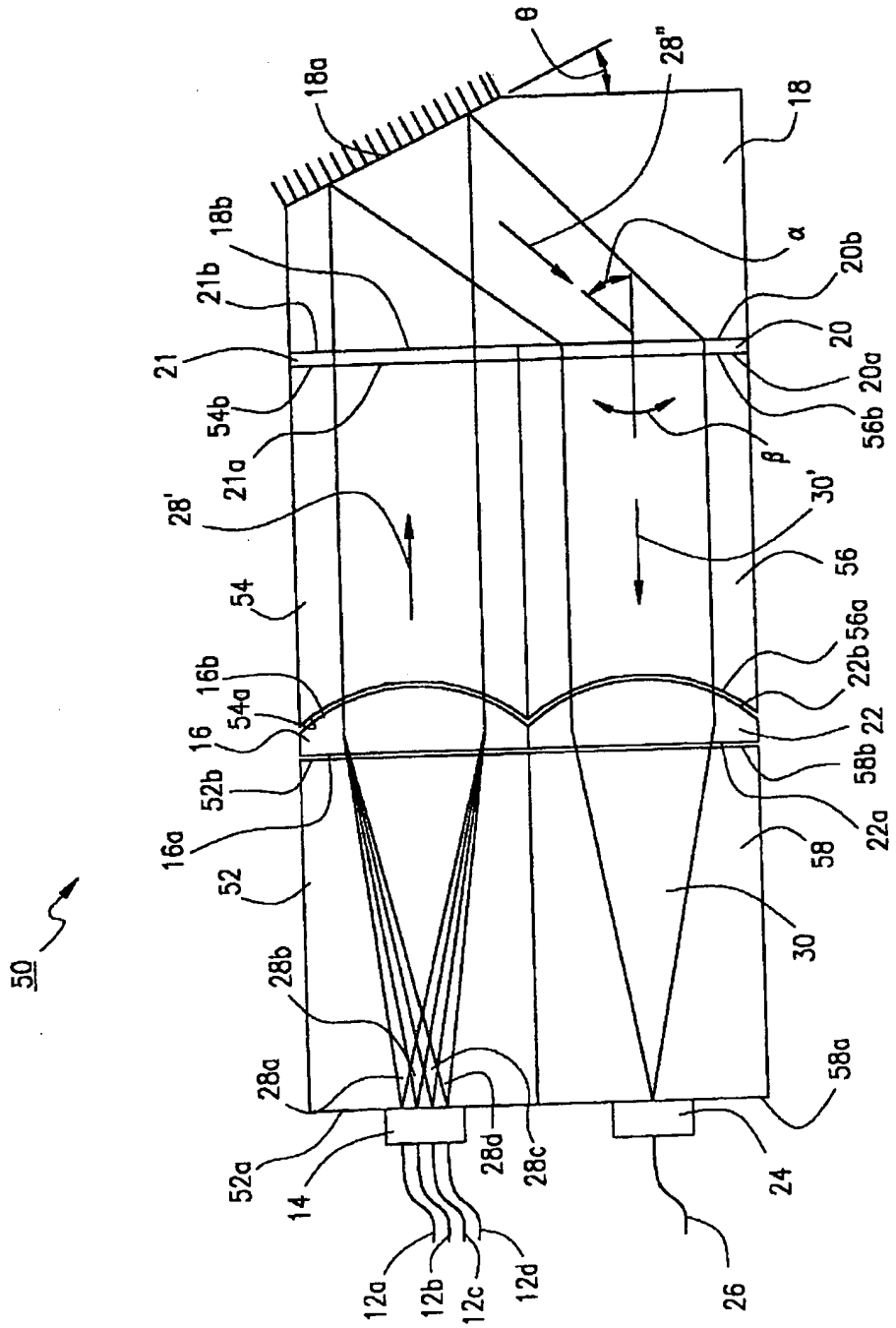

θ
28"
18a
18
18b
21b
α
20b
21
20
54b
20a
56b
β
21a
28'
30'
54
56
56a
16b
22b
54a
16
22
52b
58b
16a
22a
52
58
30
50
28b
28a
58a
52a
28d
28c
24
14
12a
12b
12c
12d
26

FIG. 4

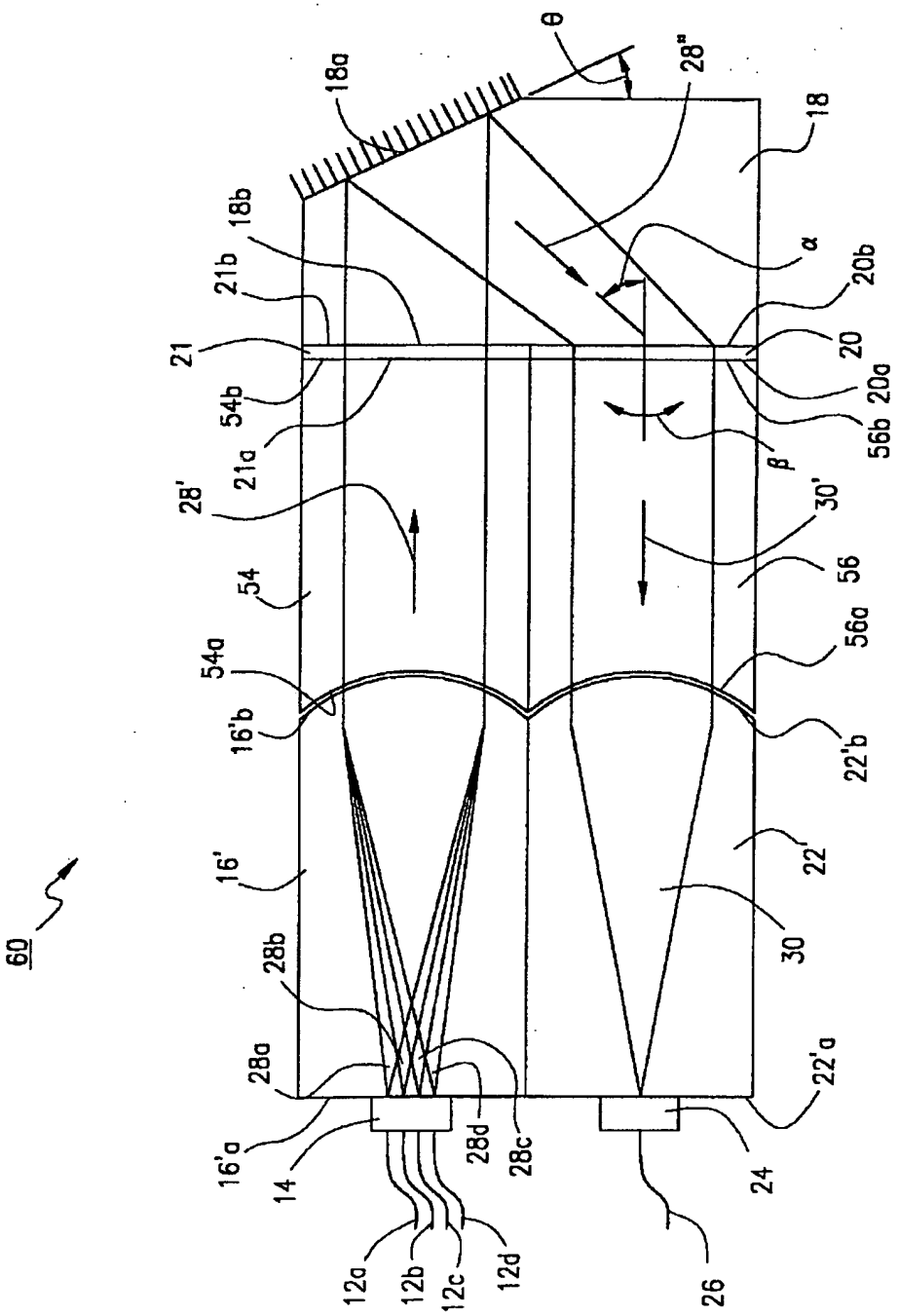

θ
28"
18a
18
18b
21b
α
20b
21
20
54b
20a
56b
21a
β
28'
30'
54
56
54a
56a
16'b
22'b
60
16'
22'
28b
30
28a
22'a
16'a
14
28d
28c
24
12a
12b
12c
12d
26

FIG. 5

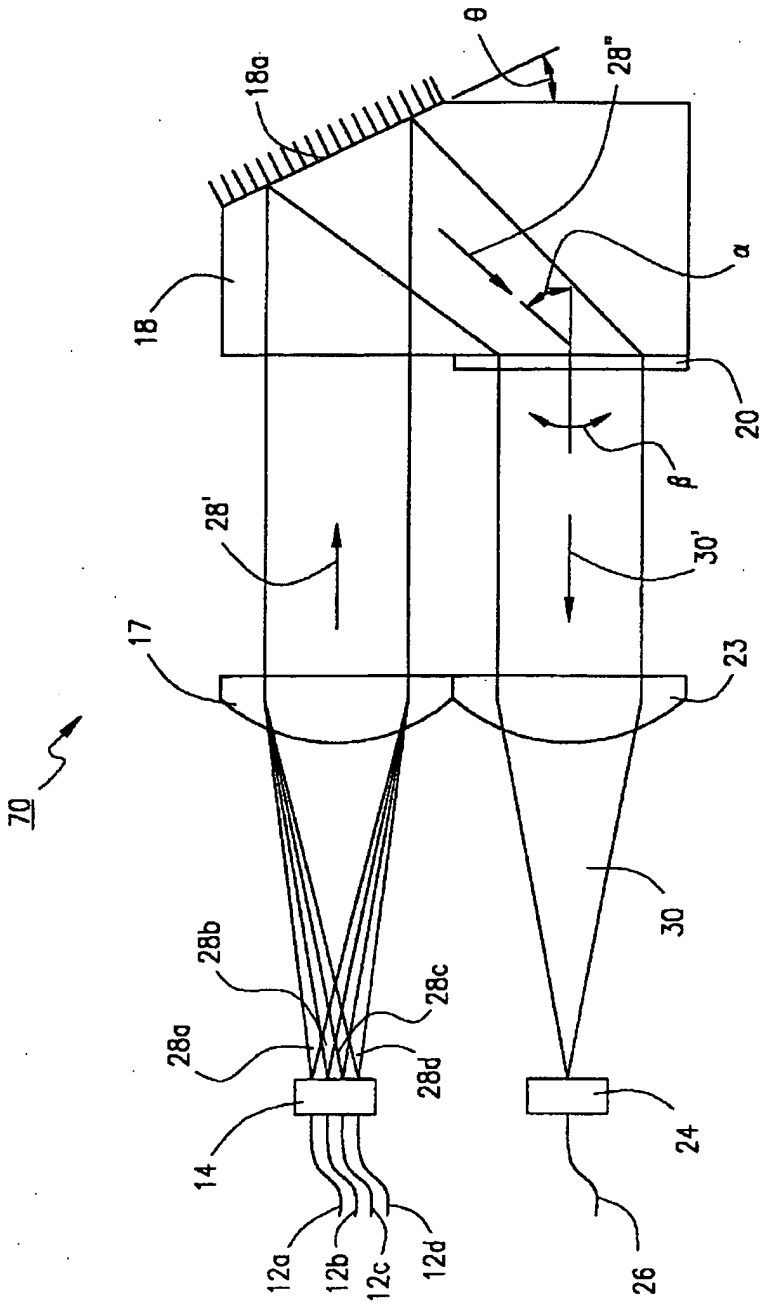

θ
18a
28"
α
18
20
β
28'
30'
17
23
70
28b
28c
28a
28d
30
14
24
12a
12b
12c
12d
26

FIG. 6

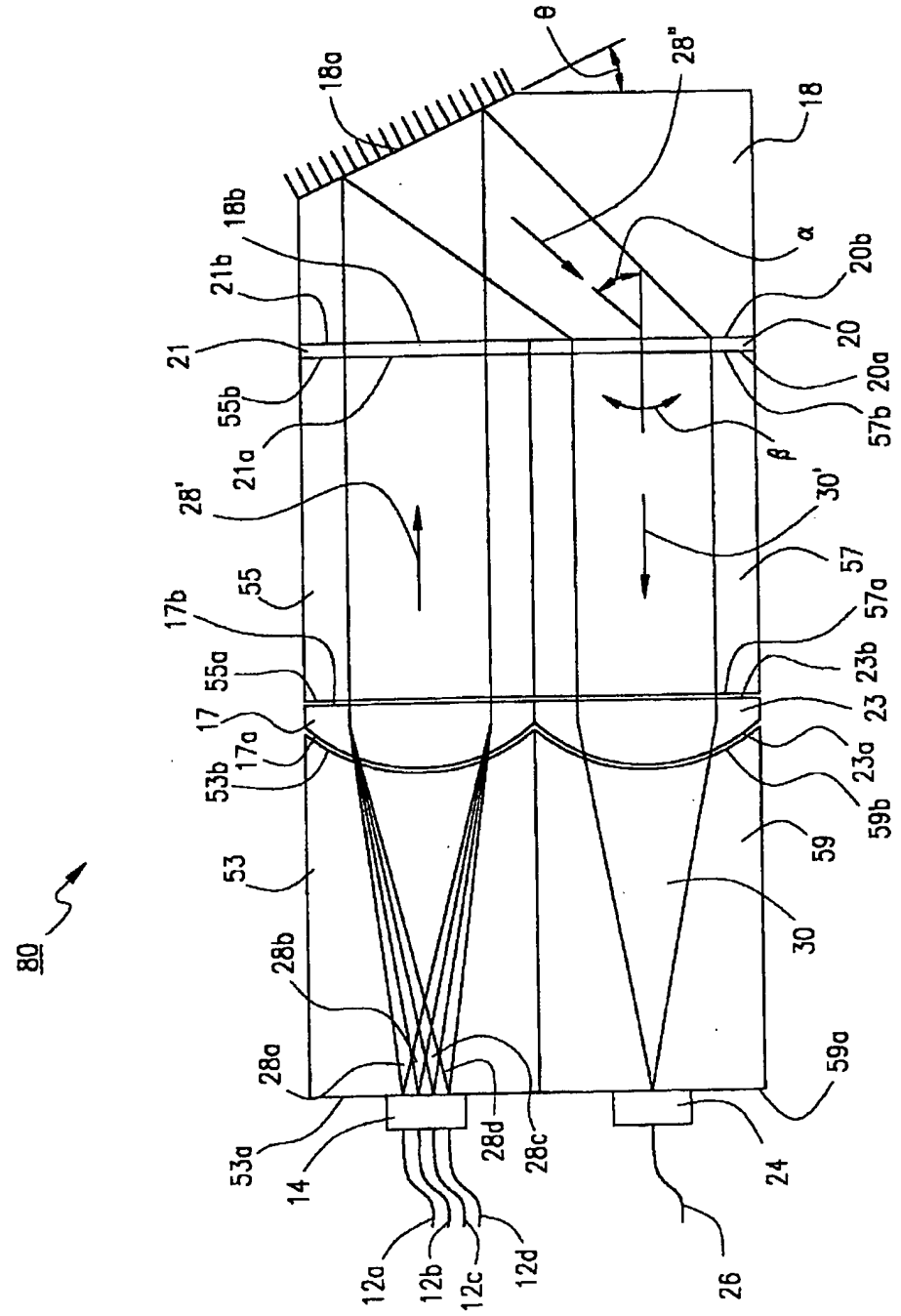

θ
28"
18a
18
18b
21b
α
20b
21
20
55b
20a
57b
β
21a
28'
30'
57
55
17b
57a
55a
23b
17
23
17a
23a
53b
59b
59
53
30
80
28b
28a
59a
53a
14
28d
28c
24
12a
12b
12c
12d
26

FIG. 7

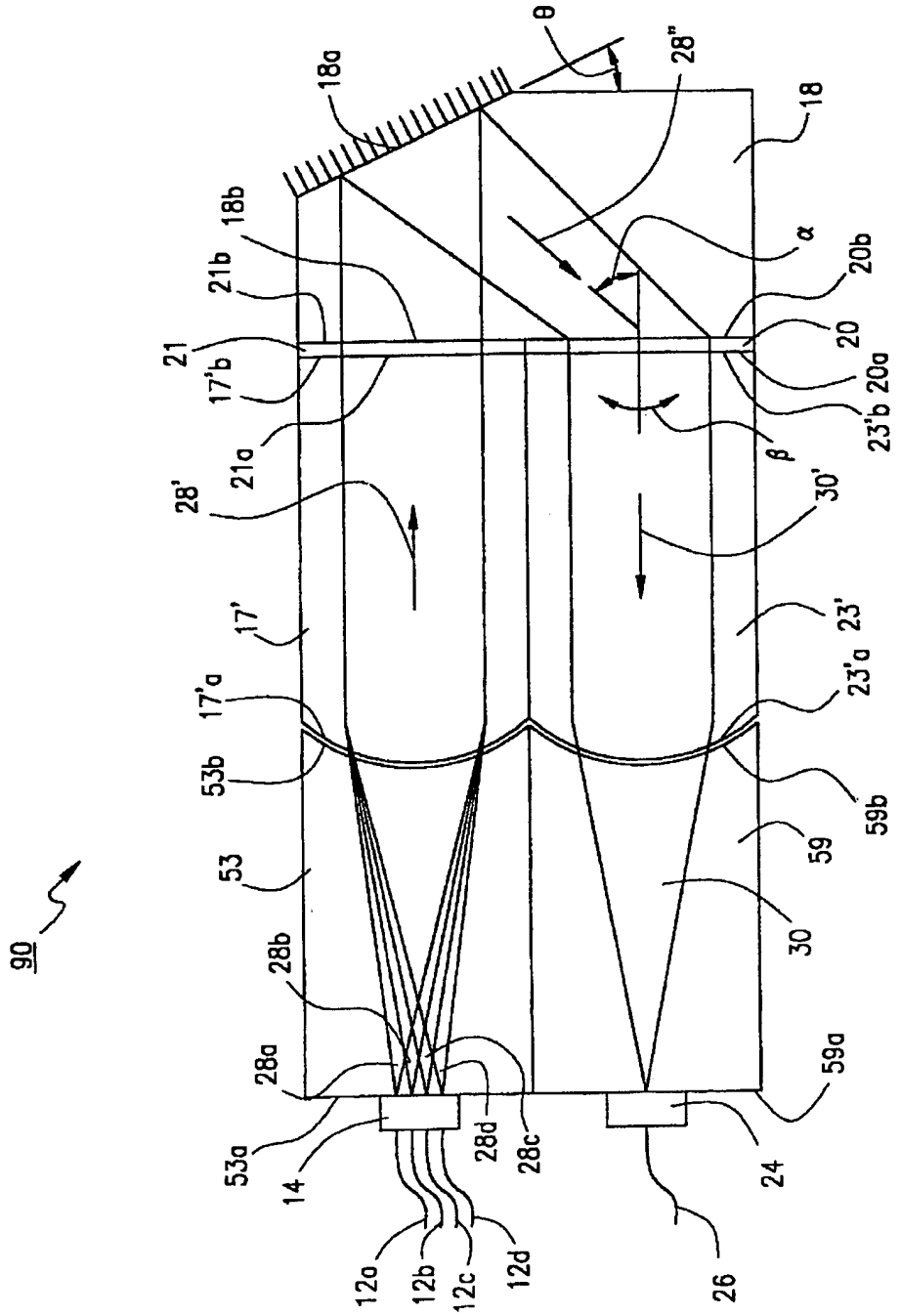

θ
28"
18a
18
18b
21b
α
20b
21
17'b
20
20a
23'b
β
21a
28'
30'
17'
23'
17'a
23'a
53b
59b
59
53
90
30
28b
28a
59a
53a
14
28d
28c
24
12a
12b
12c
12d
26

FIG. 8

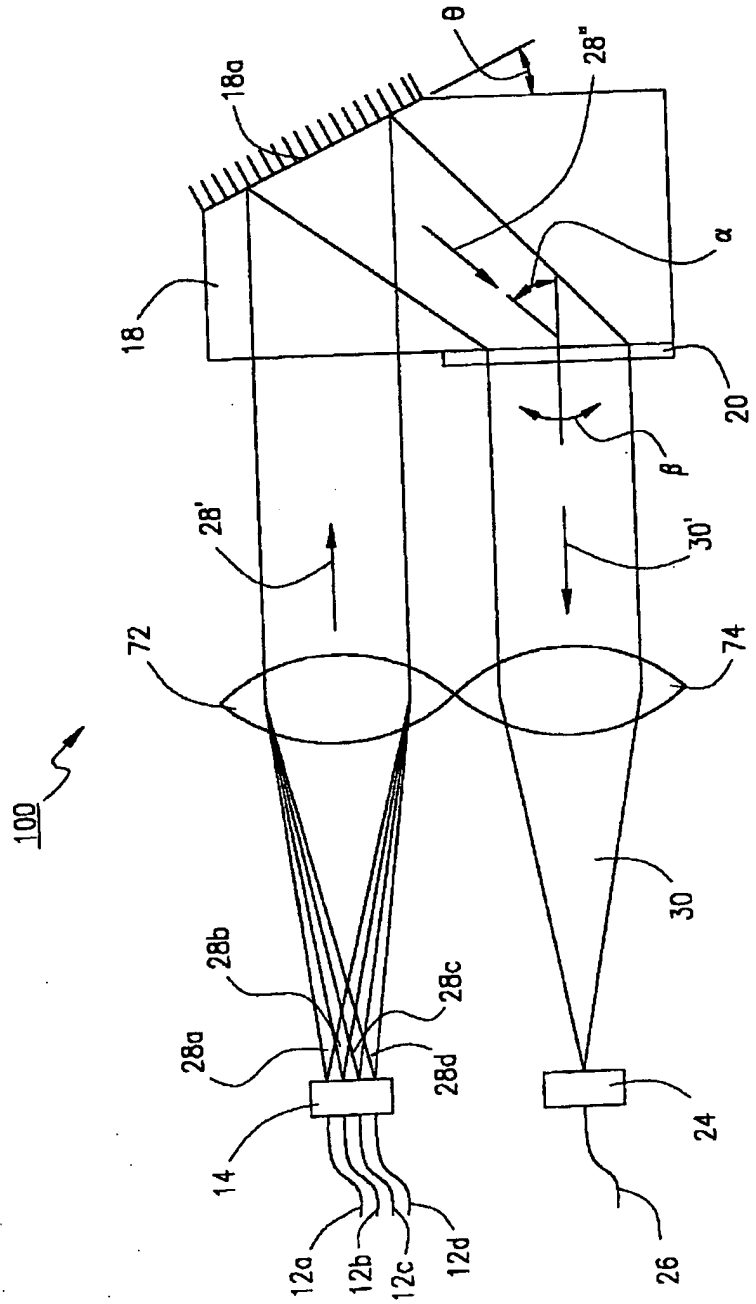

θ
28"
18a
α
18
20
β
28'
30'
72
74
100
30
28b
28c
28a
28d
14
24
12a
12b
12c
12d
26

FIG. 9

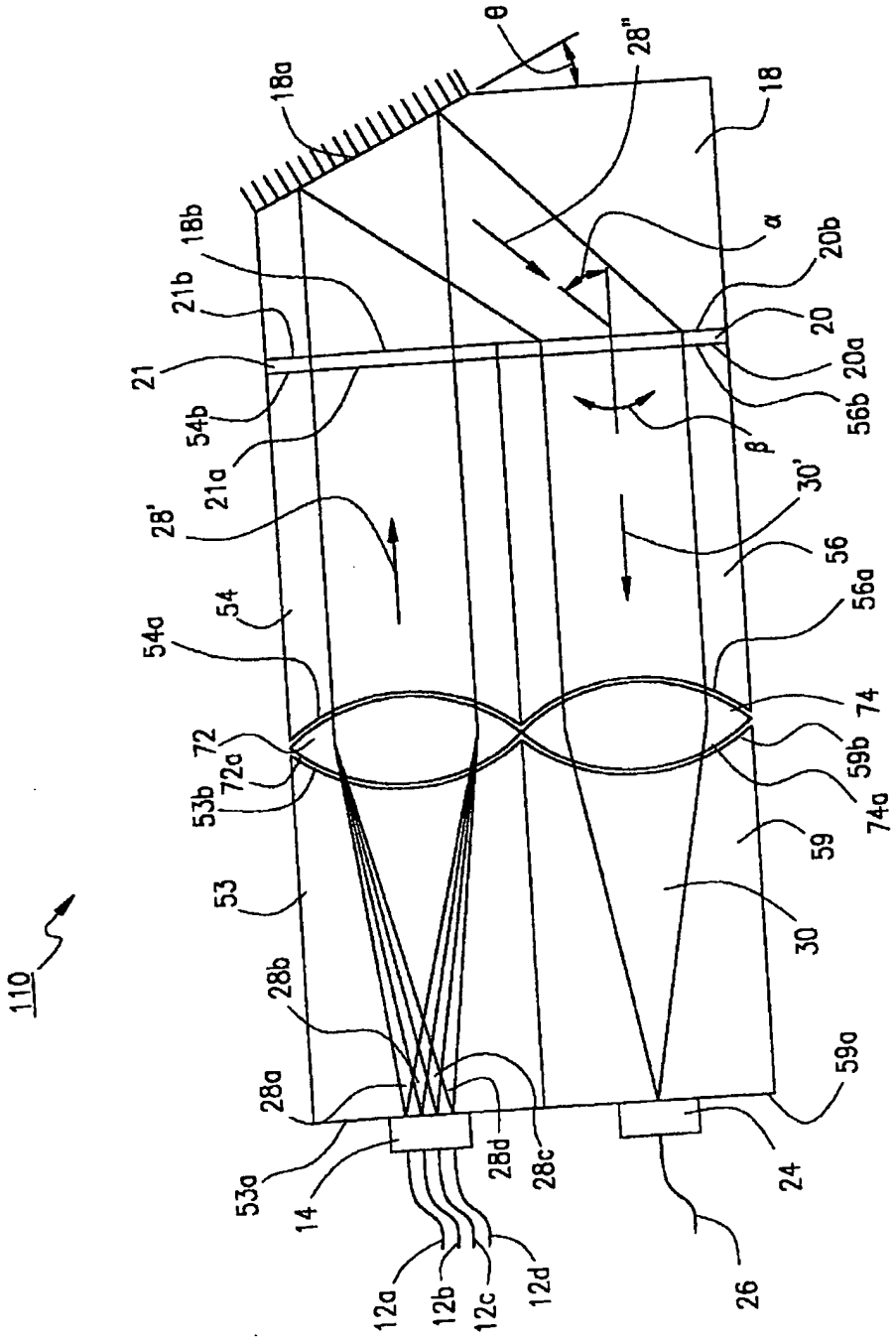

θ
28"
18a
18
18b
21b
α
20b
21
20
20a
54b
56b
β
21a
28'
30'
56
54
54a
56a
74
72
72a
59b
53b
74a
59
53
30
110
28b
59a
28a
24
53a
28d
28c
14
12a
12b
12c
12d
26

FIG. 10

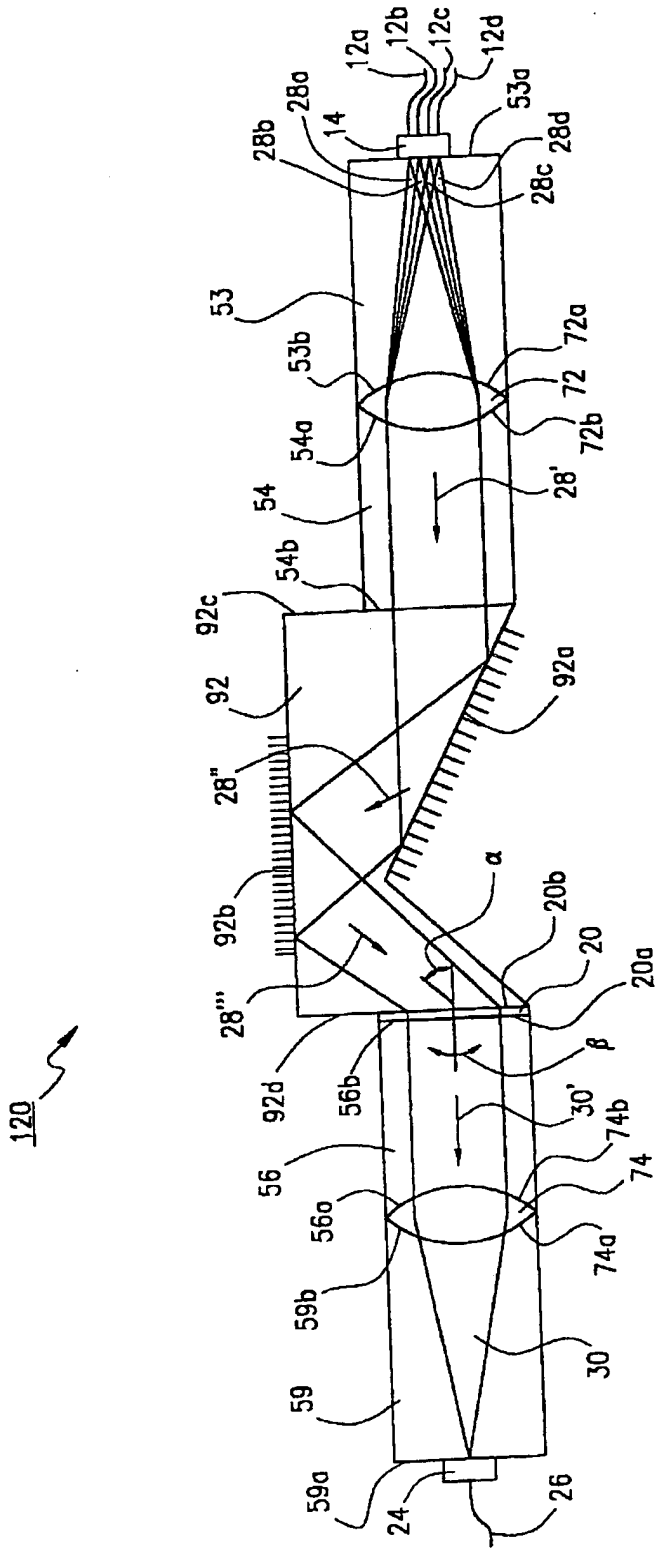

12a
12b
12c
12d
28a
28b
14
53a
28d
28c
53
53b
72a
72
72b
54a
28'
54
54b
92c
92
92a
28"
92b
α
20b
20
20a
28'''
92d
56b
β
30'
74b
74
56
56a
74a
59b
30
59
59a
24
26
120

FIG. 11

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/14815

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)
EPO-Internal, WPI Data, INSPEC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 026 131 A (JANNSON TOMASZ P ET AL) 25 June 1991 (1991-06-25) abstract; figures 1,4,7,9 column 3, line 45 - line 62 column 6, line 31 - line 68	1,2,4,7, 8,28,29, 31,34,35
X	EP 0 323 602 A (PENCOM INT) 12 July 1989 (1989-07-12) the whole document	1,2,4-6, 28,29, 31-33
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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
15 December 2000	11/01/2001

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INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A	WO 93 21548 A (VALTION TEKNILLINEN ;AIKIO MAURI (FI)) 28 October 1993 (1993-10-28) abstract; figures	1,10,22, 28,37,49
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INTERNATIONAL SEARCH REPORT

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Inter nal Application No
PCT/US 00/14815

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